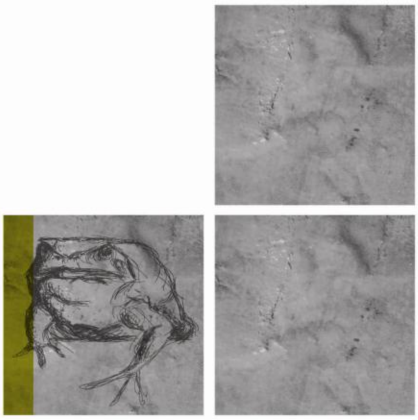

Modelling the distribution of vertebrate pests in New South Wales under climate change

Peter Caley, Philip Tennant and Greg Hood

Invasive Animals CRC

Australian Government
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Contents

Summary

This project, funded by the Invasive Animals Cooperative Research Centre on behalf of the New South Wales Department of Environment, Climate Change and Water, develops and applies tools to model the distribution and abundance of vertebrate pest species in relation to climatic and biophysical variables. Such models are needed to predict how the distribution of pest species may vary under a changing climate. We assembled a priority list of vertebrate pests affecting biodiversity in New South Wales (NSW) based on reported threats to species, populations and ecological communities. Feral goats, feral cats, red foxes, European rabbits, and feral pigs are the most common recorded threats to ‘endangered’ or ‘vulnerable’ terrestrial species in NSW, affecting 84.5% of threatened species listed.

This report covers these species—as well as cane toads, Indian mynas, starlings, wild dogs and wild deer. It uses quantitative and, where necessary, qualitative species distribution models to predict the distribution and abundance of these species using land manager desk-top surveys undertaken in 2004. Using the 2004 data, the species distribution models generally predicted the ranges of each species extremely well, but performed poorly in identifying areas where animals were considered to be at a high density. This may have resulted in part from data issues, including the effect of having multiple ‘observers’ and the scale of the analyses (5 km x 5 km grids).

These models were then used to predict the distribution and abundance of these pests under 2050 climate forecasts. Climate scenarios for 2050 were generated from four global circulation models (GCMs)—CSIRO, MIROC, ECHO and ECHAM—that performed reasonably well in modelling current Australian climate. As expected under a warmer climate, cane toads, which have tropical origins, are predicted to expand their range considerably (fourfold). Predictions varied more for species with temperate origins. Rabbits are predicted to generally decline in distribution and abundance. Foxes are predicted to increase in density in some areas and decrease in others, with their overall distribution changing little. Feral cats are predicted to have a slight decrease in abundance, but to maintain a similar range.

The current distributions of some species, such as feral pigs, wild dogs and feral goats, are affected by land use, particularly the intensity of agriculture. To make sensible predictions, therefore, changes in land use need to be modelled first. After predicting land use as a function of forecast climates, the resulting land use layers can then be fed into species distribution models. Using this modelling approach, feral pigs are predicted to change their distribution considerably, with conditions in the central western areas, east of the Darling River, becoming more favourable. This may be a result of predicted land use change. Under most of the GCMs we used, the proportion of land suitable for intensive agriculture in 2050 decreases, with a commensurate increase in the amount of land classified as suitable for extensive grazing. Such low-intensity land use appears favourable to feral pig presence. It is also considered that feral pigs have not yet fully colonised all the currently suitable habitat in NSW, particularly in coastal areas, so there will be ongoing range expansion regardless of a changing climate. The five deer species existing as free-ranging populations in NSW are predicted to have the collective ability to colonise all but

the most arid interior. Dingoes are expected to increase their range largely as a result of changing land use, and this will have implications for the distribution of goats, and possibly the abundance of the smaller deer species. The ability of the modelling process to predict the 2004 distribution of starlings was poor, so how their distribution will change in future is largely unknown.

The forecasts from GCMs are constantly changing as the models improve and emissions scenarios change, hence the predictions arising from this report should be revisited on a regular basis. To facilitate regular analysis the density and distribution of vertebrate pests needs to be quantified in a consistent, standardised manner.

1. Introduction

This project, undertaken for the Invasive Animals Cooperative Research Centre on behalf of the New South Wales Department of Environment, Climate Change and Water, seeks to develop and apply tools that can be used to minimise the threats to biodiversity and agriculture posed by introduced terrestrial animal pests in New South Wales (NSW). These threats are increasing because (1) many introduced animals have not reached the full extent of their anticipated distribution, (2) new pests are sometimes imported and some become established, and (3) it is likely that some existing pests will expand their ranges with climate change. The report applies methods for modelling the distribution and abundance of pest species in relation to climatic and biophysical variables, using readily available pest animal survey data. These methods will improve the capacity of responsible agencies to detect and respond to incursions of new, emerging, and spreading pests in response to climate change. The focus is on key terrestrial pests in NSW, although the modelling tools and techniques could be applied on a national basis.

The damage caused by pest animals in NSW and across Australia is already substantial (example for pigs in McLeod 2004, Coutts-Smith et al 2007, West 2008). Climate change might enable some pest species to expand (or contract) their range, or become more (or less) numerous within their current range. To respond to such changes, natural resource managers need the capacity to document the current extent and impacts of pest animals, describe how the extent and impacts are affected by climate and other geographically distributed variables, and make predictions of likely extent and impacts as a function of human-induced climate change.

Predicting the impact of a future climate requires that the relationship between climate and the distribution and abundance of pest animals can be adequately modelled. For some species, particularly those with life stages that have specific requirements, there may be sufficiently detailed data on their ecology and physiology to generate semi-mechanistic models of distribution. A good example of this is the cane toad (Phillips et al 2008). For most pest species this is not the case and the standard approach is to build statistical models relating pest abundance to measurable site attribute data. The process is correlative and relies on inductive inference for prediction.

Gathering data detailing species abundance over broad areas is prohibitively expensive in most cases. An alternative or an adjunct (eg Saalfeld and Edwards 2010) to designed surveys of animal density is to use the knowledge of land managers gained during their everyday travels as a means of deriving density surfaces over large areas. For example, West and Saunders (2003, 2007) estimate the density of vertebrate pest species in a semi-quantitative manner at 5 km × 5 km resolution across NSW based on expert opinion. The accuracy of maps produced by this method will vary across the landscape—land managers are typically asked to classify the abundance of pests in locations they have visited rarely, if at all, as well as those that are well known to them. Although data quality varies, the method provides two advantages over presence-only data: there is information on absences and on abundance at each site. When pest damage is related to abundance (Hone 2007), it is more informative to predict spatial changes in abundance, rather than only changes in distribution.

Disadvantages of such data may include lack of spatial resolution. For example, a spatial resolution of 5 km × 5 km may contain areas of varied topography, climate, habitat and land use. This variation within a sampling unit may hamper efforts to uncover causal relationships underlying abundance as may observer effects, whereby different observers rate density differently.

Expert-derived data are increasingly becoming the only type of data available on recent distribution and abundance of vertebrate pest species. Despite the limitations of such data sources, we need to develop methods for utilising such data to predict the distribution and abundance of pest species. This report addresses this need: it uses land manager-derived estimates of abundance to model how vertebrate pest distribution and abundance in NSW is influenced by climatic and biophysical variables, and how it will change with forecast climate change. The species covered are the cane toad (*Rhinella marina*), feral cat (*Felis catus*), feral goat (*Capra hircus*), feral pig (*Sus scrofa*), Indian myna (*Acridotheres tristis*), European rabbit (*Oryctolagus cuniculus*), European fox (*Vulpes vulpes*), starling (*Sturnus vulgaris*), wild dog (*Canis lupus dingo, C. l. familiaris*) and wild deer (species of *Cervus*, *Axis* and *Dama*). We chose these species because there were data readily available on their distribution, and they ranked highly on a list of terrestrial pest animal species considered to have deleterious impacts on biodiversity.

2. Materials and methods

2.1 Prioritising vertebrate pests

2.1.1 Impacts

The threatened species profiles for terrestrial fauna species developed by the NSW Department of Environment, Climate Change and Water were used as a means of examining the threat of vertebrate pests to biodiversity. Each profile contains a list of threats that was developed by a combination of literature review and the opinion of professionals working in the field (www.threatenedspecies.environment.nsw.gov.au). The impact on biodiversity of individual pest species was estimated by tallying the number of times each pest is listed as likely to have deleterious effects on threatened species. Of the existing vertebrate pests in NSW, feral goats, feral cats, introduced foxes, rabbits, and feral pigs are listed most commonly as threats to those native terrestrial species in NSW listed as either ‘endangered’ or ‘vulnerable’, and account for 84.5% of all listings (Table 1). Wild dogs (including dingoes and hybrids with domestic dogs), macropods, black rats, feral horses, wild deer and cane toads are listed less frequently. As Table 1 shows, the threats to biodiversity posed by human land use outweigh those from vertebrate pests.

Table 1. Distribution of threats by pest species and threat listing on a species basis for NSW. Data is derived from Department of Environment, Climate Change and Water (DECCW) threatened species profiles for terrestrial species (DECCW 2008).

threat	all listings	critically endangered	endangered	vulnerable
1. pest species				
feral goat	75	0	52	23
feral cat	68	0	30	38
fox	65	0	29	36
rabbit	62	0	39	23
feral pig	58	4	29	25
wild dog*	17	0	7	10
macropods	14	0	9	5
black rat**	12	0	4	8
feral horse	11	2	4	5
wild deer	5	1	3	1
cane toad	1	0	0	1
total	388	7	206	175
2. other threats				
habitat clearing/ modification	565	3	292	268
grazing	276	3	155	115
fire	283	2	141	139
weeds	266	3	139	122
other	627	9	331	286

* lack of wild dogs resulting in higher [threatening] density of cats and foxes was noted for some threatened species

** threats predominantly confined to offshore islands

2.2 Modelling present vertebrate pest distribution

2.2.1 Choice of species to model

Of the pest species listed in Table 1, a NSW-wide survey of land managers during 2004 (West and Saunders 2007) provided data on distribution and abundance during 2004 of nine species (or groups): feral pigs, feral goats, wild deer, foxes, rabbits, wild dogs, feral cats and cane toads. Deer species were included in the current study because their distribution is expanding rapidly. Invasion and establishment of the cane toad is listed as a key threatening process under NSW legislation (DECCW 2009a). No introduced birds were listed as threats to biodiversity, but the Indian myna was included because of its widely postulated potential to threaten native fauna species. Although there is limited evidence in the literature of its deleterious impacts on native species, its aggressive behaviour, competitive use of tree-hollows for breeding, and apparent increasing distribution suggest it may pose a serious threat to biodiversity in the future, if it does not already (Hone 1978, Martin 1996, Pell and Tidemann 1997).

2.2.2 Base data on species distributions

The 2004 land manager survey of West and Saunders (2007) provided data on the feral cat, wild dog, feral pig, feral goat, fox, rabbit, cane toad and wild deer; Point-locality data for the Indian myna, starling and corresponding survey locations were obtained from Birds Australia. The data were received from the NSW Department of Industry & Investment in a fishnet-polygon GIS format, comprising about 33 000 cells across the state.

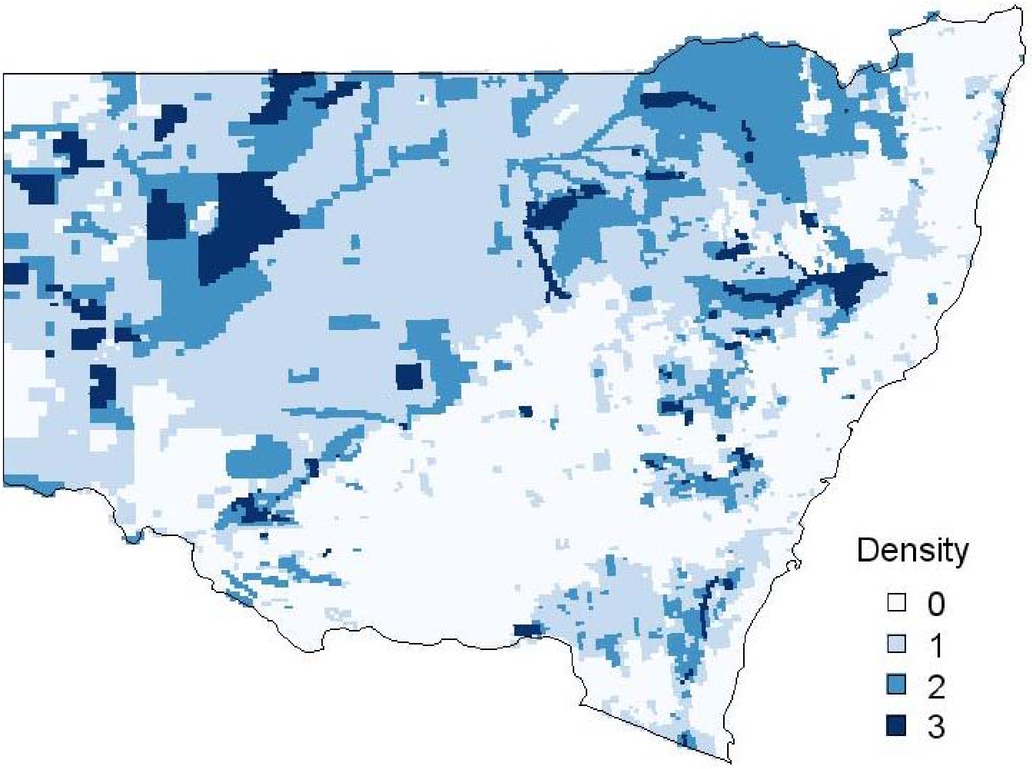
The 2004 land manager survey

The 2004 land manager survey of West and Saunders (2007) used qualitative criteria to create an ordinal scale of pest animal density across NSW. The criteria (Table 2) are consistent with those used for previous surveys in NSW during 2002 (West and Saunders 2003), and also successfully applied in Western Australia (Woolnough et al 2004). Seasonal variations in pest animal populations were not considered in the abundance estimates. In total, 125 land managers assisted in the survey mapping—86 rangers from the 48 Rural Lands Protection Board districts and 39 pest management staff from the NSW National Parks and Wildlife Service, State Forests of NSW, Game Council of NSW, and Environment ACT.

Table 2. Density/abundance criteria for pest animals used by West and Saunders (2007). Scores assigned for modelling are in parentheses.

density	definition
high (3)	Many animals seen at any time and much sign of activity ie animals always observed, reliable sightings or otherwise evidence of high abundance. Best described as observing significant evidence of many animals on greater than 80% of occasions.
medium (2)	Some animals seen at almost any time and/or much active sign ie frequent but unreliable sightings of animals. Best described as observing significant evidence of some animals on 50–80% of occasions.
low (1)	Few or no sightings and/or little active sign ie rare sightings / evidence. Best described as observing very little evidence of animals on 1–50% of occasions
absent (0)	No animals ie very unusual to see evidence of animals. Best described as seeing either no evidence or very little evidence of extremely low numbers of animals on less than 1% of occasions.

The survey method raises several difficulties for fitting statistical models and drawing firm conclusions. Although the criteria are intended to provide a quantitative basis, it is unknown how the density classifications relate to true density. Second, the estimates of density (and hence model errors) are undoubtedly spatially autocorrelated, with neighbouring cells expected to have more similar density classifications than distant cells. There is also a degree of uncertainty in that experts were assigning animal densities to cells which they have never visited, or haven’t visited recently. Differences in pest visibility with differing habitat types also presents challenges to providing standardised density classifications state-wide. The many extended straight boundaries in density changes, particularly in western areas of NSW (Map 1) suggest a resolution in the data of less than the 5 km × 5 km scale attempted. Changes in actual density are unlikely to be as linear in space as these boundaries suggest (except, of course, where exclusion fencing exists or where habitat features are linear).



Map 1. Example of the base data on pest density: Density of feral pigs in New South Wales estimated during the 2004 land manager survey of West and Saunders (2007).

Bird survey data

The data from Birds Australia on the Indian myna and starling was a list of sightings at known locations. From this list, systematic records which had moderate to high geographical reliability were retained for analysis. That is, 'Incidental search' survey type were excluded, as were records from accuracy distance classes 'within 50 km' and 'coordinates to be checked'. Systematic records included those of survey type '2-ha Search', 'Fixed-route Monitoring' and 'Area Search'. Records used dated from 1996 to 2008.

For both bird species, a table of point coordinates (or 'bird point layer') was produced indicating presence or absence at each systematic survey location (date/location). Within a GIS, each bird point layer was overlayed with the approximate 5 km x 5 km fishnet polygon layer and a bird recording rate calculated as the proportion of survey sites where each species was detected. This recording rate functioned as a crude measure of density. Where polygons did not overlap with any survey sites, a status of 'no data' was assigned to that polygon cell.

2.2.3 Explanatory variables

Explanations for the distribution of each pest species were sought using a combination of climate, geographic variables and (for some species) by their interaction with other vertebrate pests.

Selecting explanatory climate variables

Nineteen bioclimatic variables (Table 3) for current climate conditions using the BIOCLIM (Nix 1986) definitions were sourced from WorldClim online (Hijmans et al 2005). The data were collated and re-sampled to overlay the original pest layers. The climate layers were based on interpolated average monthly climate data commonly drawn from the years 1960–1990.

Table 3. Derived bioclimatic layers used in the random forests classification model.

BIO1	annual mean temperature
BIO2	mean diurnal range [mean of monthly (max temp - min temp)]
BIO3	isothermality (BIO2/BIO7) (* 100)
BIO4	temperature seasonality (standard deviation *100)
BIO5	max temperature of warmest month
BIO6	min temperature of coldest month
BIO7	temperature annual range (P5-P6)
BIO8	mean temperature of wettest quarter
BIO9	mean temperature of driest quarter
BIO10	mean temperature of warmest quarter
BIO11	mean temperature of coldest quarter
BIO12	annual precipitation
BIO13	precipitation of wettest month
BIO14	precipitation of driest month
BIO15	precipitation seasonality (coefficient of variation)
BIO16	precipitation of wettest quarter
BIO17	precipitation of driest quarter
BIO18	precipitation of warmest quarter
BIO19	precipitation of coldest quarter

Selecting explanatory biophysical variables

A selection of GIS layers considered to be potentially relevant in describing the distribution and abundance of vertebrate pests were collated. These layers were commonly at a 1 km resolution and the mean, median or modal value for the overlain 5 km × 5 km pest density layer was used in analysis. Potential explanatory variables made available for analysis are listed in Table 4.

Table 4. Biophysical explanatory variables used in statistical modelling.

GIS variable	name	source/resolution
Carb A	soil organic carbon (A horizon)	Modelled organic carbon from the National Land and Water Resources Audit with a grid resolution of 0.001 degrees.
Soil H_20 N	soil nitrogen (A horizon)	Modelled weight percentage nitrogen in soil. NLWRA dataset with grid resolution of 0.001.
Elevation	elevation	AUSLIG 9 second DEM (Version 2) of Australia.
Soil bulk density	soil bulk density (A horizon)	Derived from soil map data and interpreted tables of soil properties for specific soil groups. NLWRA dataset with grid resolution of 0.001.
Dist to water	distance to water	The minimum of distance to lakes and distance to bore where lakes and bores based on GEODATA TOPO 250K Series 3 data.
Soilm_mean	Mean soil moisture	Mean annual soil moisture 1980–2006
Mean NPP	Mean net primary productivity (MODIS)	MODIS net primary productivity. Mean of annual measurements 2000–2006 (tons/ha/yr).
Mean NDVI	Mean normalised difference vegetation Index (NDVI)	A measure of the density and vigour of green vegetation growth using measurements from satellite-housed advanced very high resolution radiometer (AVHRR).
Mean ARIA	remoteness	Mean value of Accessibility /Remoteness Index of Australia (ARIA+).
VAST2	vegetation modification	Vegetation assets, states and transitions classification orders vegetation by degree of anthropogenic modification through 5 classes from residual (base-line) to total removal. ‘Bare ground’ is an additional class. Cell size equals 1 km.
L_USE_1	land use	Catchment scale land use mapping (CLUM), October 2008. Year of base-line catchment scale mapping ranged from 2000 to 2008. Collapsed into 6 land use classes (conservation, grazing unmodified pastures & forestry, grazing modified pastures, intensive agriculture, industrial, water). Cell size equals 50 m.
Slope	slope	Slope (ninesecond DEM v2). Cell size equals 1 km.
Soilm_cv	coefficient of variation—soil moisture	Coefficient of variation of annual soil moisture – 1980–2006.
Pop_density	population density (2006)	Mean population density per square kilometre. Originally by ABS collection district.

SOIL_CAP	soil capability	7 classes of soil suitability for agricultural production. Very high (1) to very low (7).
SOIL_TYPE	soil type	13 classes of soil type from the digital Atlas of Australian Soils (Aug. 2004).
PR_INT_AG	intensive agriculture	The proportion of intensive agriculture (IA) in a 5 x 5 km cell where IA is classed as the CLUM categories 3.3–3.5, 4.2–4.6, 5.1 and 5.2.
PR_INT_AG2	intensive agriculture	IA also includes grazing modified pastures (3.2) in addition to 3.3–3.5, 4.2–4.6, 5.1 and 5.2.
PR_WOODYVG	woody vegetation	Proportion of native extant woody vegetation in a 5 x 5 km cell. Includes forest, woodland, heathland and shrubland associations.
MVG	Vegetation (code)	Major vegetation groups (MVGs). Developed from the National Vegetation Information System. 21 classes. Cell size equals 1 km.
MVG_DESC	Vegetation (description)	MVGs. Developed from the National Vegetation Information System. 21 classes. Cell size equals 1 km.
SHADE	Vegetation offering shade	Binary variable where cell = 1 where most of the 5 x 5 km cell is covered by native extant vegetation offering shade, cell = 0 otherwise. Based on MVGs 1-17.
PR_SHADE	Vegetation offering shade	Proportion of native extant vegetation offering shade in a 5 x 5 km cell. Based on MVGs 1–17.

Choosing interspecific interactions

Competitive interactions can markedly influence species realised or actual distributions. Table 5 details interactions capable of changing a density classification. Effects that are unclear (conflicting direction of effects among studies, or study findings possibly confounded) are considered a non-interaction (in the interests of parsimony). Interactions to include were chosen by reviewing the relevant literature for each species. Where effects described in the literature ranged from neutral to significant (as in the case of wild dog–fox interactions) the interaction was included. Interactions where an interaction was possible but unproven were also included. For example, Letnic et al (2010) found no effect of dingo absence on cat abundance, although low dingo abundance correlated with higher fox abundance and vice versa, whereas Burrows et al (2003) found that combined control of both dingoes and foxes resulted in an increase in cat abundance. In both studies it is unclear whether dingoes and/or foxes reduce cat numbers, and if so, by what mechanism (competition for food or agonistic behaviour between the species). Corbett (1995b) found dingoes were unable to regulate wild pig populations, however this does not rule out some degree of limitation, and hence effects of abundance. Mynas, starlings and toads were considered not to have any important interspecific species interactions. Table 5 suggests that the dingo is a strongly interacting species (Soule et al 2005).

Table 5. Matrix of potential species interactions. The column heading of each row is the species that was included during the model fitting process as explanatory variables for the species given by the row heading. The distribution and abundance of cats, dingoes and foxes, for example, was considered to potentially influence the distribution of rabbits and vice versa.

	cat	dingo	fox	goat	pig	rabbit	deer
cat	na						
dingo	yes[1,9]	na					
fox	no	yes[1,7,8]	na				
goat	no	yes[4,5]	no	na			
pig	no	yes[6]	no	no	na		
rabbit	yes[11]	yes[10]	yes[11]	no	no	na	
deer	no	yes	no	no	no	no	na

[1]Letnic and Koch (2010); [2]Pech et al (1992); [3]Banks et al (1998); [4]Caughley et al (1980); [5]Parkes et al (1996); [6]Corbett (1995b); [7]Johnson and VanDerWal (2009); [8]Mitchell and Banks (2005), [9]Burrows et al (2003), [10]Corbett and Newsome (1987), [11]Newsome et al (1989)
na not applicable

Accounting for changes in land use

The current distributions of some species, such as feral pigs and feral goats, are affected by land use, particularly the intensity of agriculture. To make sensible predictions for such species, changes in land use that could occur as a result of climate change need to be modelled. To do this the distribution of land use in 2008 was modelled (Table 4) using the methods outlined in Section 2.3, and the predicted distribution of land use in 2050 was used for prediction of species distributions (see below).

2.2.4 Model choice

Rather than being obtained through systematic field survey, the data in this study represent opinions of local experts on the density of pests in each local area. Their beliefs are based on practical on-ground knowledge and their understanding of a district's geography and natural resources. The subjectivity of the expert's beliefs means that their estimates of pest density in any grid square do not directly measure animal abundance on the ground. As a result, the models built are based on data that represents a combination or synthesis of knowledge from the land managers involved in the study.

To derive this summary, a technique called 'random forests' (Breiman 2001), a form of data mining, was used which would be expected to perform as well as any other ensemble method such as boosted regression trees (Hastie et al 2009). Briefly, a random forest model is fitted by fitting modified classification and regression tree (CART) models to bootstrapped versions of the dataset, thus generating a 'forest' of trees. The modification to the CART model involves choosing a random subset of the explanatory variables to be considered for each 'split'. For classification, the 'forest' of trees each cast a vote for the predicted class, and the average across all trees is used. Presence/absence modelling tools such as MAXENT (Phillips et al 2006) were not considered because these are not designed to handle response variables with more than two categories. With four levels of density class provided, it was felt that it would be wasting information to reduce it to presence/absence data only. However, presence/absence models were fitted to enable model performance to be compared (see below). All statistical analysis was done using the R statistical environment (R Development Core Team 2009).

The standard implementation of the random forest method (package `randomForest`) was used rather than the method implemented within the `party` package (Hothorn et al 2010), although the latter is believed to give less biased estimates of importance (Strobl et al 2009). This was because the `party` package, which produced similar results, required excessive computing time. Default settings were chosen for the number of variables randomly sampled as candidates and the minimum size of terminal nodes. The number of trees to grow in a run was set at 200, which should be sufficient to minimise misclassification errors and computation time (Hastie et al 2009).

Whilst the random forests models provide ‘importance’ measures of the explanatory variables, which in essence are the frequency by which the various variables are included in the models, these measures are not reported here. This is because the chosen data mining approach seeks to maximise predictive power at the expense of understanding causation.

2.2.5 Data suitability by species

It became apparent during the course of the modelling process that the distribution data for some species precluded the use of statistical modelling for prediction. In particular, the recent rapid spread of wild deer species indicates they have not yet realised their potential ranges, and so any prediction of future distribution based on their current distribution in NSW would be premature (and hence biased). In addition, the species of deer was not always known with certainty. The same problem of expanding range applies to feral pigs in parts of NSW: they are slow to spread into new ranges (Caley 1997), and deliberate releases are the source of most new populations (Hone and Waithman 1979, Spencer and Hampton 2005).

There is a different problem with using the current distributions of feral goats and dingoes as a basis for model fitting. Their realised niches are much smaller than their fundamental niche (their potential role in the landscape), arising from spatial variation in human tolerance and associated management (and, for goats, the presence of dingoes), which are essentially competitive interactions. Quantifying competition from humans over large areas—which is affected, for example, by hunting pressure and land use—is difficult because it depends on the attitudes of individuals. The effect of ‘known’ management is also uncertain: the dingo fence once reliably delineated dingo presence and absence (Caughley et al 1980), but this no longer appears to be the case (Pople et al 2000, Wallach et al 2009). Because of these difficulties, the 2008 and 2050 estimates of land use were used as surrogates for human activity, although it is accepted that land use will be a poor predictor of human behaviour towards vertebrate pests.

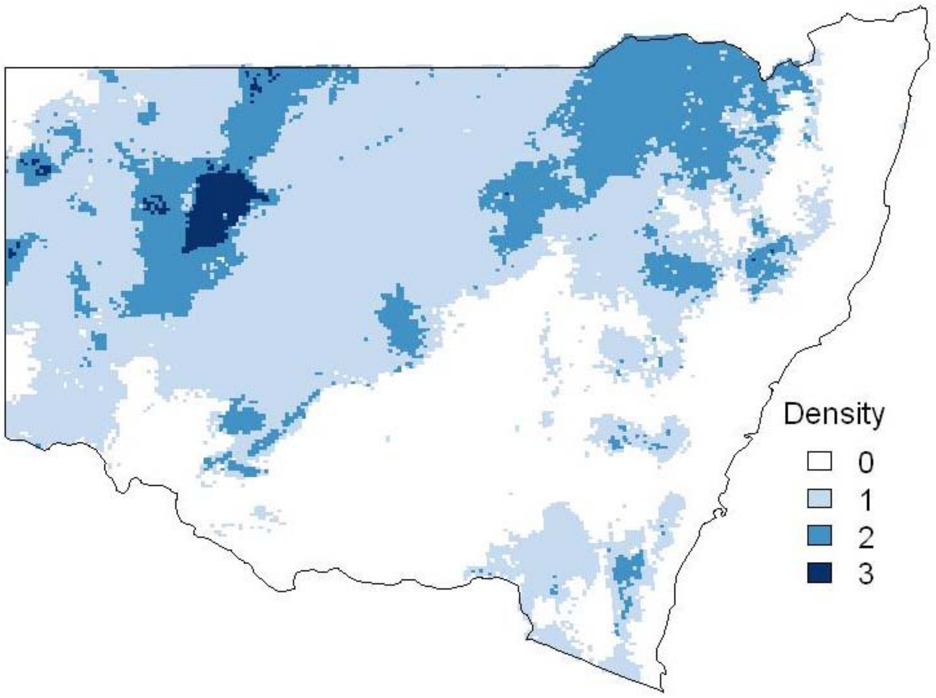
A final caveat on the data suitability is that the distribution of some species (particularly feral pigs) may vary widely in response to a run of good or bad seasonal conditions. Hence the distribution and abundance of species as elicited by the land managers may be better modelled by weather variables recorded over a shorter time period (eg Caley 1993, Choquenot 1998). However, modelling the effects of short term weather patterns on species distribution and abundance addresses a different question to quantifying the effects of climate change.

2.2.6 Data selection

The nature of the spatial layout of the data—a 5 km x 5 km fishnet polygon—meant the individual fishnet cells were not independent; spatial correlation is present among both the explanatory (biophysical and climate variables) and response (pest density or occurrence) variables. This creates problems with estimation techniques that assume independence (Bahn et al 2008). Rather than incorporate the spatial correlation of a response variable with only four values into the statistical modelling process, sub-sampling of the 33 000 fishnet polygon cells was undertaken to reduce the spatial correlation in the data. Ten non-overlapping subsets (folds) of data were selected in a semi-regular, spatially separated manner, each with about 1500 cells.

2.2.7 Assessing model fit

Model performance was assessed by classification error rates when modelling the four density classes, and classification and area under the receiver operating characteristic curve (AUC) when modelling presence/absence data. A 'model averaged' prediction for each species in each cell was obtained by combining the results obtained from the 10 fold-based models fitted to each of the 10 folds of data (Map 2). Further details are given in the Appendix.



Map 2. Modelled density of feral pigs during 2004 based on the cell-based average of the 10 sampling folds. Compare with Map 1 for the 2004 base data drawn from the land manager desktop survey.

2.3 Predicting future pest distribution

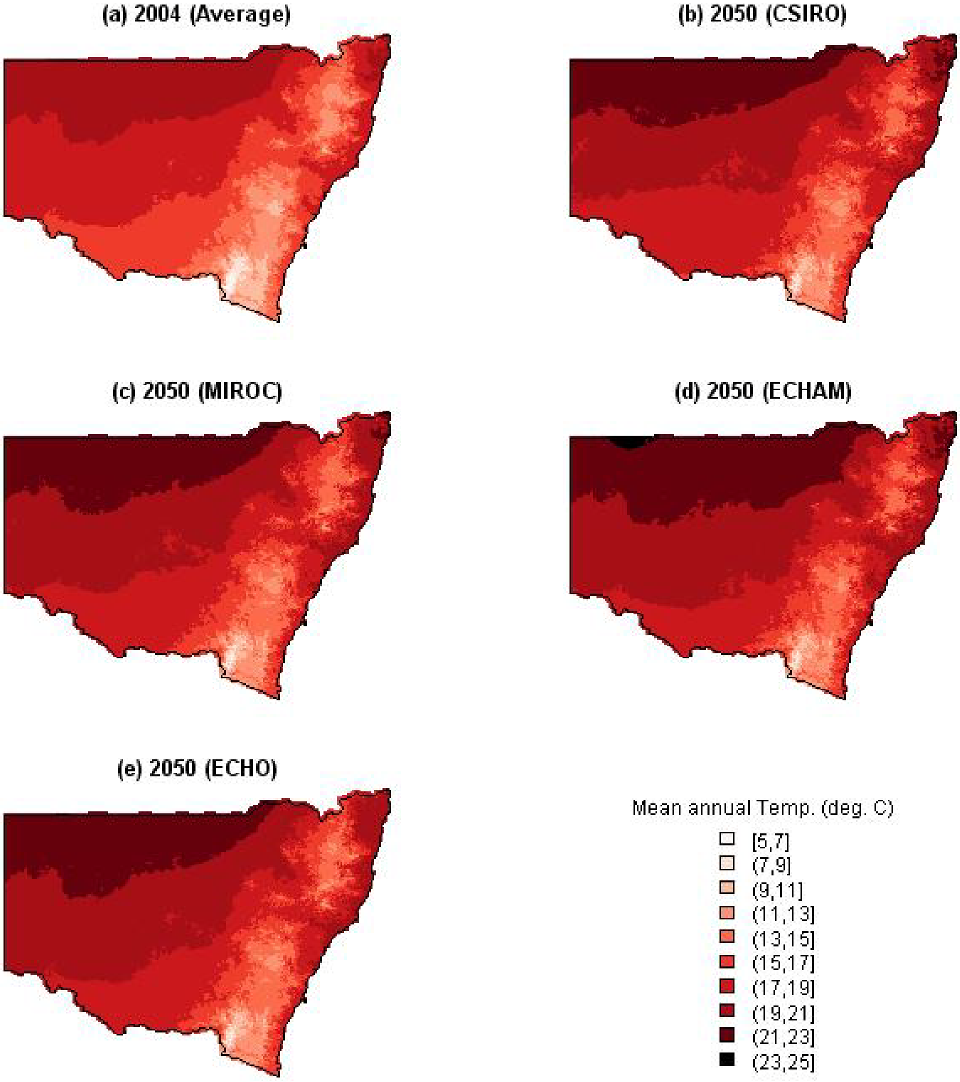
2.3.1 Choice of climate models for prediction

To explore changes in pest distribution under future climate scenarios, downscaled future climate predictions were used from selected global climate models (GCMs) from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007). Projections of future climates used in this report represent the A2a (medium–high) emission scenario for 2050. These four climate models were chosen as a basis for 2050 projections because they performed relatively well in an assessment of simulated current precipitation, maximum temperature and minimum temperature over Australia (Perkins et al 2007). The GCMs used were: i) csiro_mk3_0 (CSIRO); ii) mpi_echam5 (ECHAM, Max-Planck-Institut fur Meteorologie); iii) miub_echo_g (ECHO-G, Meteorological Institute of the University of Bonn); and iv) miroc3_2_medres (MIROC-m, Centre for Climate Systems Research, University of Tokyo; National Institute for Environmental Studies; Frontier Research Centre for Global Change). The four GCMs are referred to hereafter as CSIRO, ECHAM, ECHO and MIROC, respectively. BIOCLIM variables (Nix 1986) for the above GCMs were downloaded directly from the International Centre for Tropical Agriculture (CIAT) website (Downscaled GCM Data Portal online http://gisweb.ciat.cgiar.org/GCMPage/). As with the current climate conditions layers, data were re-sampled to overlay the original 5 km by 5 km pest density layer.

Global circulation models (GCMs) are constantly being improved and their forecasts are changing—the modelling in this report is designed so that it can be rerun on a regular basis if climate forecasts change.

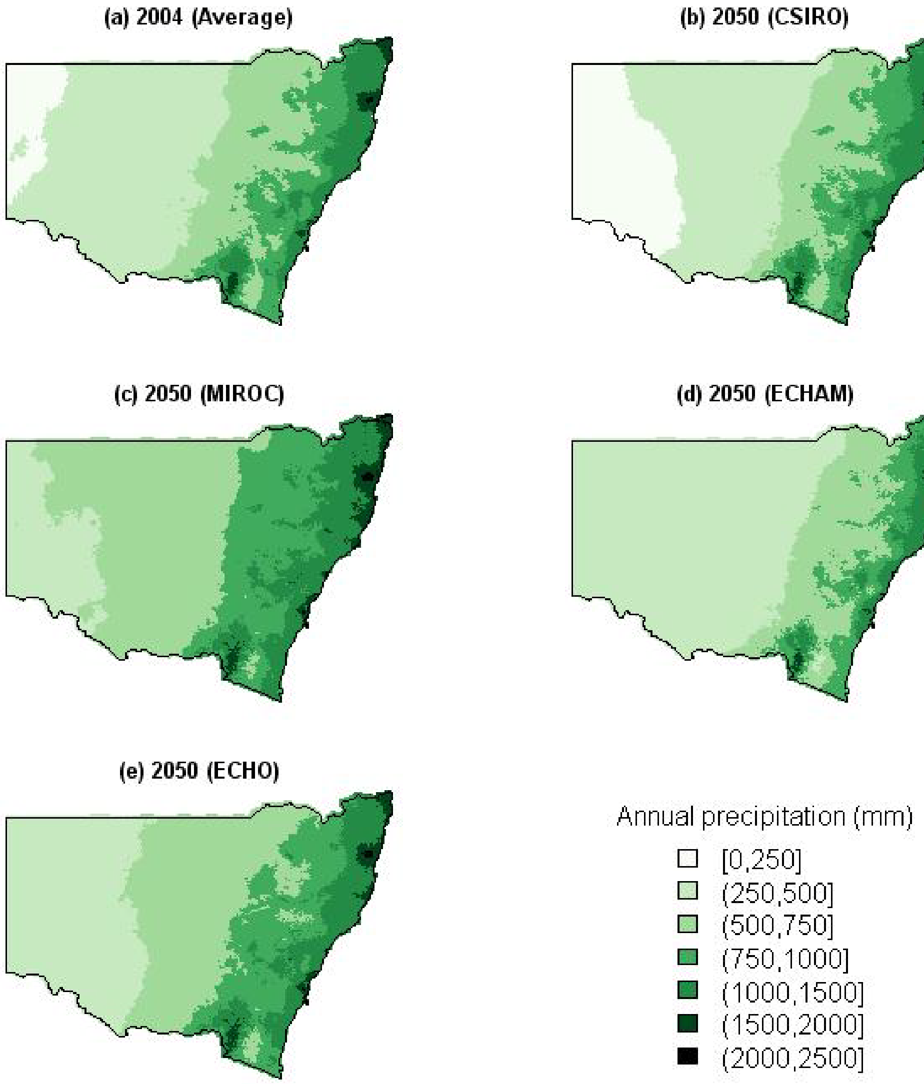
2.3.2 Climate forecasts for 2050

The forecasts from the four climate models were very similar by some measures, and differed substantially for others. For example, the forecast annual mean temperature differed little between the models, with the average increase across all cells of 1.7 to 2.3 ^{O}C (Map 3).



Map 3. Distribution of the baseline (2004) and forecast mean annual temperature for 2050 based on a medium–high emissions scenario. The interval notation (7,9] is equivalent to 7 < temp ≤ 9.

In contrast, the forecast distribution of annual precipitation differed substantially between the models. In particular, precipitation was forecast to increase substantially based on the MIROC (mean increase across all cells 189 mm) and to a lesser extent ECHO (mean increase across cells 112 mm) models, but to decrease based on the CSIRO (mean decrease 30 mm) and ECHAM (mean decrease 31 mm) models (Map 4).



Map 4. Distribution of the baseline (2004) and forecast mean annual precipitation for 2050.

2.3.3 The sequence of steps taken to predict 2050 distributions

Because the distribution of some vertebrate pests depends on land use and, potentially, on the distribution of other pests, a four step process was used to build quantitative species distribution models (SDMs) and forecast species distribution and abundance under each GCM:

1. Prediction models, each consisting of 10 fold-based models from which a single model-averaged prediction for each cell could be obtained, were built for land use and each pest species using the current climate and biophysical variables (Table 3 and Table 4).
2. The land use prediction model was used to predict land use in 2050 using climate variables for 2050 SRES A2a and with biophysical variables remaining fixed. Effectively fixed land uses (eg national parks, urban, etc.) also remained fixed.

3. Predictions for non-predators were made using three sets of predictors: 2050 forecast land use, the fixed set of biophysical variables, and the 2050 SRES A2a climate variables.
4. Predictions for predators (dogs, foxes and cats) were made using the same set of predictors used in step 3, augmented by the predictions for rabbits in 2050.

'Ensemble' plots of pest species abundance and modelled differences are presented which represent the 'average' of the fitted values from each of the four climate models. The 'average' or ensemble forecast plots were produced using the rounded arithmetic mean density (0–3) from each of the GCMs. Where mean density had a remainder of 0.5, density values were alternately rounded up or down to systematically rather than randomly produce integer density values.

2.3.4 Qualitative approach

For feral goats, wild pigs, wild deer and dingoes, qualitative predictions of their future distribution are additionally made based on expected changes in land use. This was either because the species distribution was not at equilibrium, or because it was consider unfeasible to generate GIS layers that would adequately represent the competitive interactions that currently limit their range. Qualitative predictions are less testable than those derived from a quantitative model, but are also subject to a less restrictive framework, and can therefore account for factors for which extensive spatial data are unavailable.

Furthermore, whilst direct effects of climate change on vertebrate pests will be difficult to predict in many cases, changes in agricultural land use resulting from a changing climate may be relatively easy to predict, and known associations between land use and vertebrate pest distribution can be used for prediction under future climates.

3. Results

3.1 Species distribution model performance

The SDMs using random forests generally had very high performance as measured by the area under the receiver operating characteristic curve (AUC). This was consistently above 90% for all species except for starlings (Table 6). Note, however, that the models were not nearly as good at identifying the individual density class, with a particularly high error rate when trying to classify high density (Class 3) cells (Table 6).

Table 6. Misclassification percentages by density classification (0-3) or presence/absence. AUC refers to the area under the receiver operating characteristic curve for presence/absence modelling. Presence data were obtained by collapsing density classes 1–3 into a single presence class.

species	**density class**				**presence/absence**		
	0	1	2	3	absence	presence	AUC
cane toad	0.01	100	#	46.7	0.0	45.7	0.996
cat	91.8	4.4	56.7	76.0	0*	0*	*
dingo	4.8	44.8	35.1	78.3	7.0	18.9	0.958
goat	4.1	4.7	34.0	60.6	6.8	19.5	0.961
rabbit	33.3	8.1	68.6	98.6	38.4	5.5	0.930
pig	11.8	23.1	55.6	76.5	17.7	8.5	0.961
myna	na	na	na	na	1.3	58.6	0.925
starling	na	na	na	na	19.5	49.0	0.755
fox	72.0	33.0	7.2	44.9	83.7	0.1	0.988

no records of moderate density for toads
* few if any true absences of feral cats in NSW
na not applicable (density classes not measures)

3.2 Land use changes

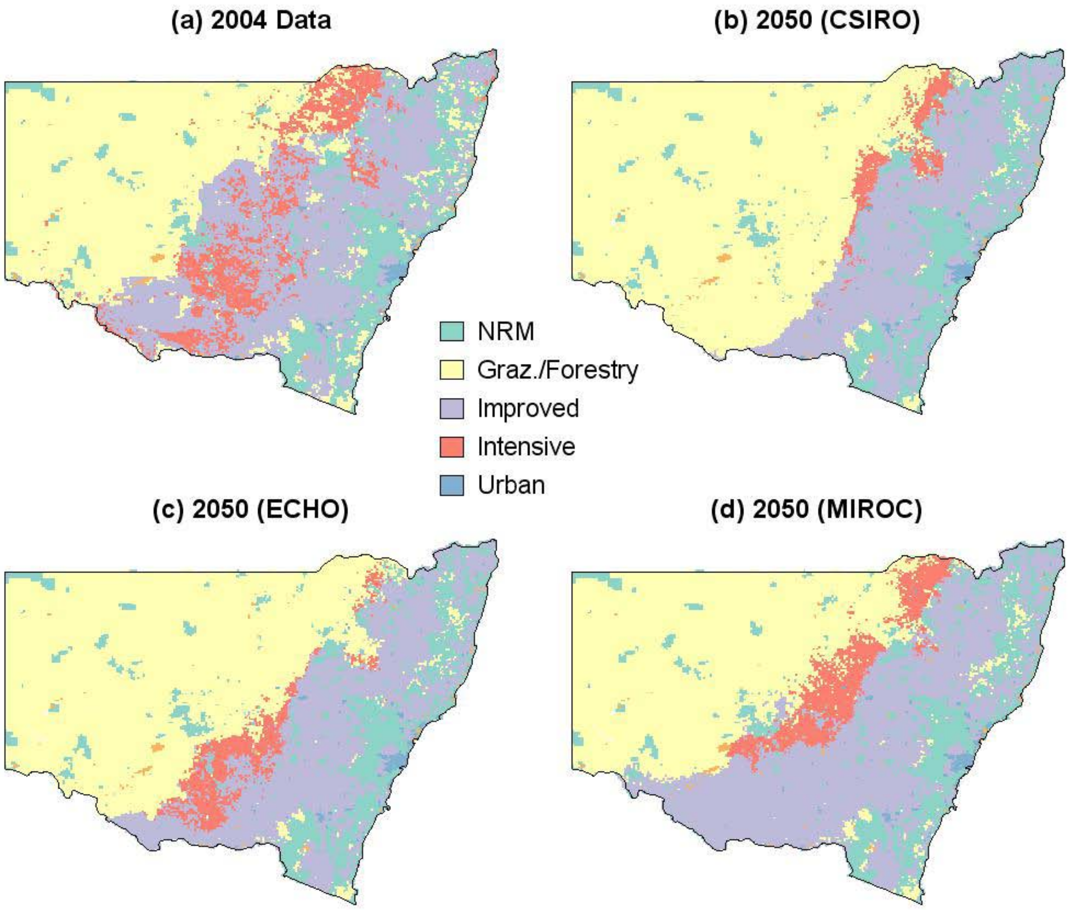
Quantitative (model-based) predictions

The model classified current land use moderately well. Land used for forestry and grazing unmodified pastures was predicted well (9.2% classification error) as was land used for grazing improved pastures (11.4% classification error). The model predicted intensive agricultural land use poorly (50.7% classification error). A likely cause for this is that the availability of irrigation water was not explicitly included as a predictor variable—such water availability allows land to be used for intensive irrigation when other factors suggest it is unsuitable.

Land use is forecast to change substantially under all four climate models considered (Table 7), with the proportion of land classified as forestry and grazing of natural vegetation increasing, and the area under improved pasture and intensive agriculture decreasing. The area of NSW used for extensive grazing of unmodified pastures, encompassing what is currently known as the Western Division is forecast to expand towards the coast under three of the four GCMs investigated (Map 5). We caution against taking the spatial forecast of the area suitable for intensive agriculture too seriously, as the model performs poorly when classifying this land use type. However, the direction and size of the change in areas suitable for intensive agriculture are noteworthy, except under the MIROC model. This exception is probably because the MIROC model predicts substantial increases in annual precipitation across most of NSW.

Table 7. Forecast changes in the three broad land use classes in NSW as of 2050 based on four different climate models under a medium–high emissions scenario. Results are based on random forests using 200 trees.

	climate model					
land use	2004	CSIRO	ECHAM	MIROC	ECHO	ALL
forestry and grazing of natural vegetation	47.4%	69.2% (+)	70.0% (+)	52.0% (+)	63.9% (+)	63.8%
grazing improved pastures	42.8%	27.8% (–)	24.8% (–)	40.8% (–)	31.2% (–)	31.1%
intensive agriculture	9.8%	3.0% (–)	5.2% (–)	7.2% (–)	4.9% (–)	5.1%



Map 5. Distribution of land use in 2004, and predicted for 2050 under forecast climates. The forecast for the ECHAM global circulation model (not shown) is very similar to that of the CSIRO model.

Qualitative (literature-based) predictions

Land use in NSW will change as a direct result of:

- biophysical changes from a changed climate
- changing costs of production arising from a) the imposition of a price on greenhouse gas emissions, in combination with b) the long-term trend for increased costs of carbon-intensive inputs (fuel, fertiliser and chemicals)
- changing commodity prices, including increases that may more than compensate for higher input prices

- competition with other land uses that act to mitigate CO_2 emissions.

Sheep (on both dry-land and irrigated pastures), cattle (dry-land and irrigated), dairy (irrigated) and grain (dry-land) enterprises are considered to be highly to very highly vulnerable to the biophysical impacts of predicted climate change. Enterprises already close to the edge of the ideal climatic range for their dominant agricultural activity are particularly at risk (Garnaut 2008). Decreases in water availability and increases in the price of water will cause some areas currently under irrigation to convert to dry-land enterprises. Increasingly, areas of land considered marginal for farming will be used as carbon sinks and/or added to the conservation estate. For example, the 90 000 hectare Toorale Station on the Darling River was purchased in 2008 by the Federal Government and most of it added to the national reserve system.

Economic modelling (eg Garnaut 2008) predicts that emissions-intensive industries, like coal, may fund forestry operations to offset their pollution levels if a price on CO_2 emissions is set. Lawson et al (2008) estimate it would be economic for as much as 26 million hectares of additional forest to be planted across Australia (about 10% of total farmland) before 2050. The extent and location of this tree planting would be sensitive to the price of CO_2 emissions. At a low price, much of this predicted tree planting would be in the higher rainfall areas of NSW and Queensland, though in the less productive parts (Burns et al 2009). As the price on CO_2 emissions increases, a marked increase in the proportion of land with potential for afforestation in lower rainfall areas is projected, with much of this on marginal agricultural land (Burns et al 2009). Additionally, agricultural land, both productive and marginal, is predicted to continue to be transformed to hobby farms (the ‘tree-change’ phenomenon), particularly in the peri-urban fringe (Luck et al 2011). The expected afforestation would increase the distribution of available refugia for some vertebrate pest species and change the type of pest management systems in place.

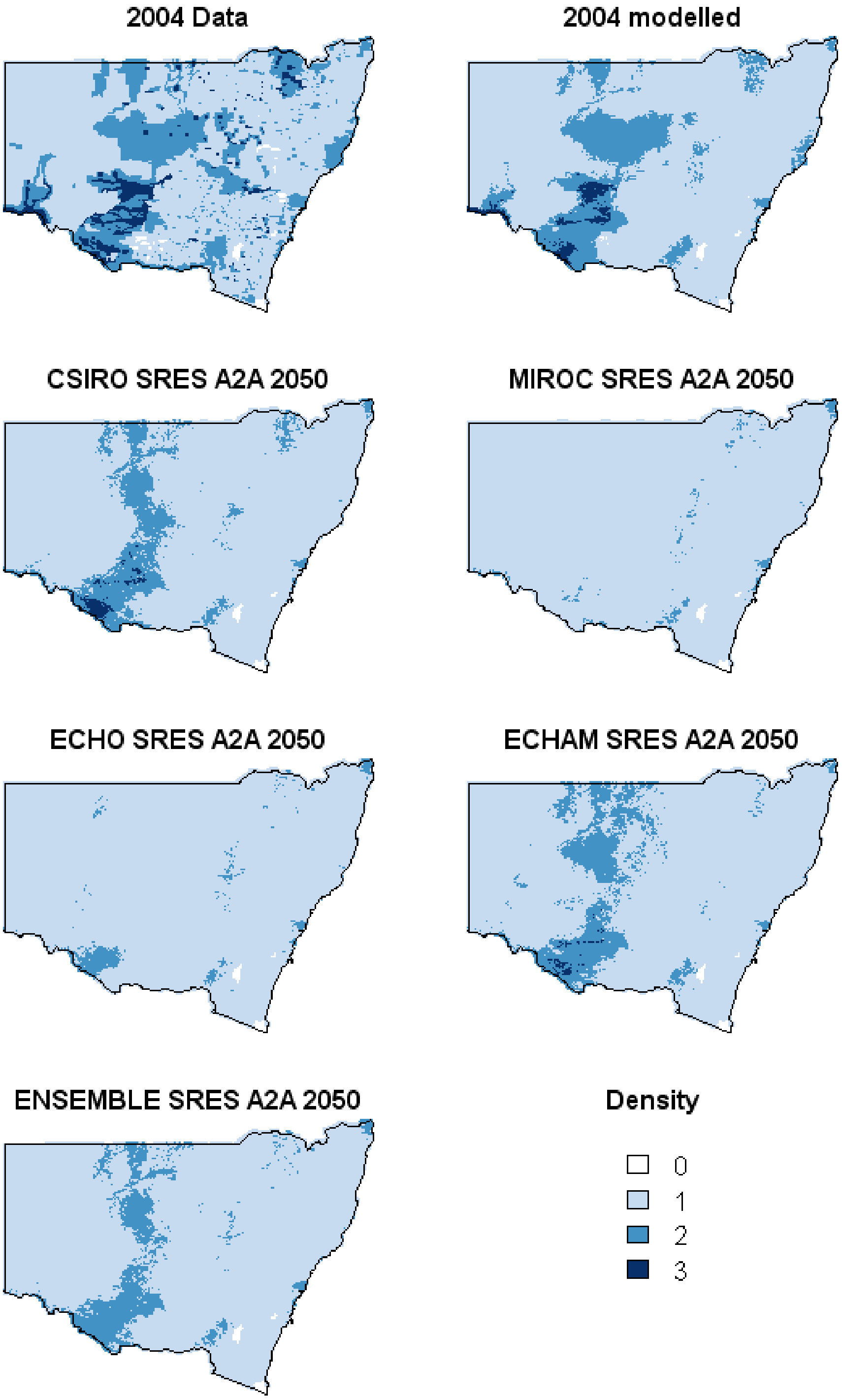
3.3 Results for individual species

For each species the first map image plots the 2004 survey data (‘2004 Data’), modelled 2004 survey data (‘2004 modelled’), forecast density in 2050 using each GCM for the chosen emissions scenario (‘CSIRO SRES A2A 2050’ etc) and averaged (‘ensemble’) forecast for the four GCMs. A second map image gives the forecast differences in pest animal density between the 2004 data and the 2050 scenarios, by individual GCM and for the ensemble forecast. It also shows changes by density class. Where a qualitative evaluation is made (wild dogs, feral pigs, feral goats, wild deer), this follows the quantitative results.

3.3.1 Feral cats

Quantitative SDM predictions

Feral cats were considered to occur in all but 0.4% of cells during the 2004 survey, with densities considered highest in the south-west plains (no data was collected for the ACT) (Map 6). All climate models forecast a substantial decrease in the area of moderate and high cat density, with a commensurate increase in low cat density (Table 8).

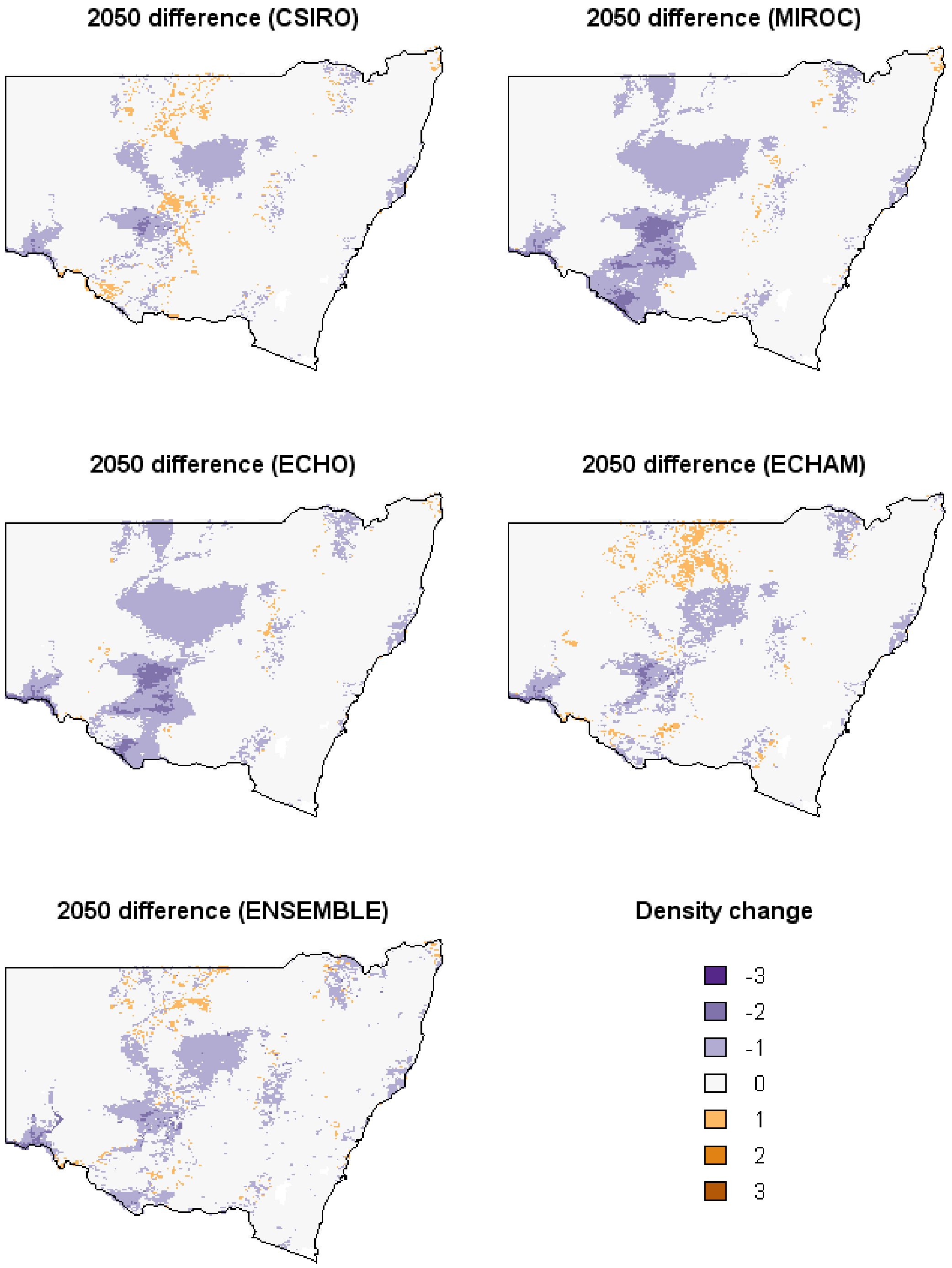


Map 6. For feral cats, the observed density (‘2004 Data’), modelled density (‘2004 modelled’), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario (‘CSIRO SRES A2A 2050’ etc), and ‘ensemble’ (‘averaged’) forecast from the four models for 2050 (‘ENSEMBLE SRES A2A 2050’).

Table 8. Changes in forecast density class of feral cats. Absolute change (%) is simply the difference between the two columns 2004 (modelled) and Ensemble. Relative change (%) is the proportion of absolute change to the 2004 (modelled) distribution.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	0	0	0	0	0	0	0	na
1	80.9	87	86.8	98.3	97.4	92.4	11.5	14.2
2	17.5	12.4	12.9	1.7	2.6	7.4	-10.1	-57.7
3	1.6	0.6	0.2	0	0	0.2	-1.4	-87.5

Most forecast changes in feral cat density tended to occur on the western slopes

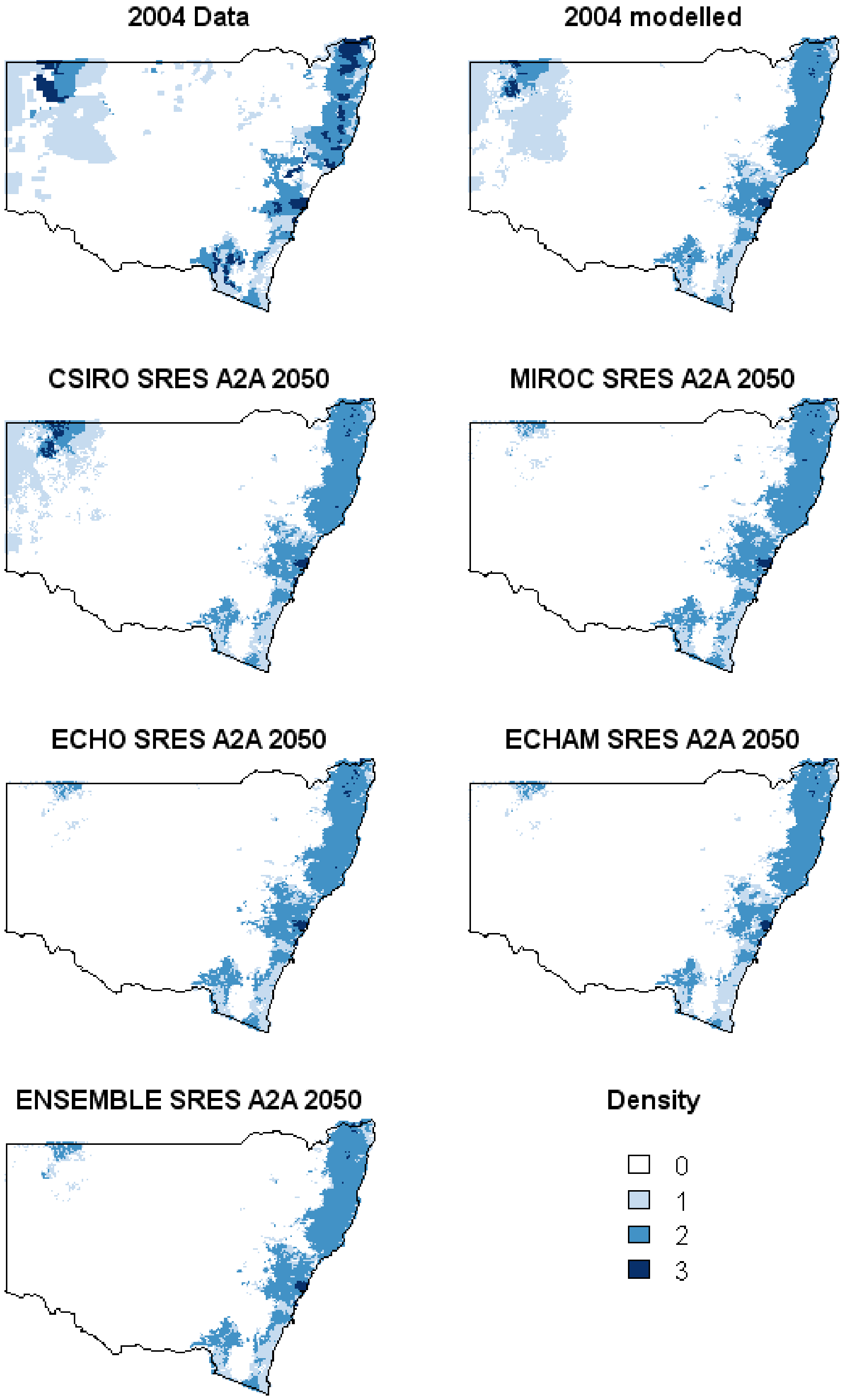


Map 7. Differences between the 2004 survey density of feral cats and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario. The purplish-blue shade '-2' represents a predicted reduction in density by 2 levels from the *modelled* 2004 abundance (top right-hand plot in Map 6). For example, the modelled 2004 density is predicted to fall from 'high' (3) to 'low' (1) under 2050 scenarios.

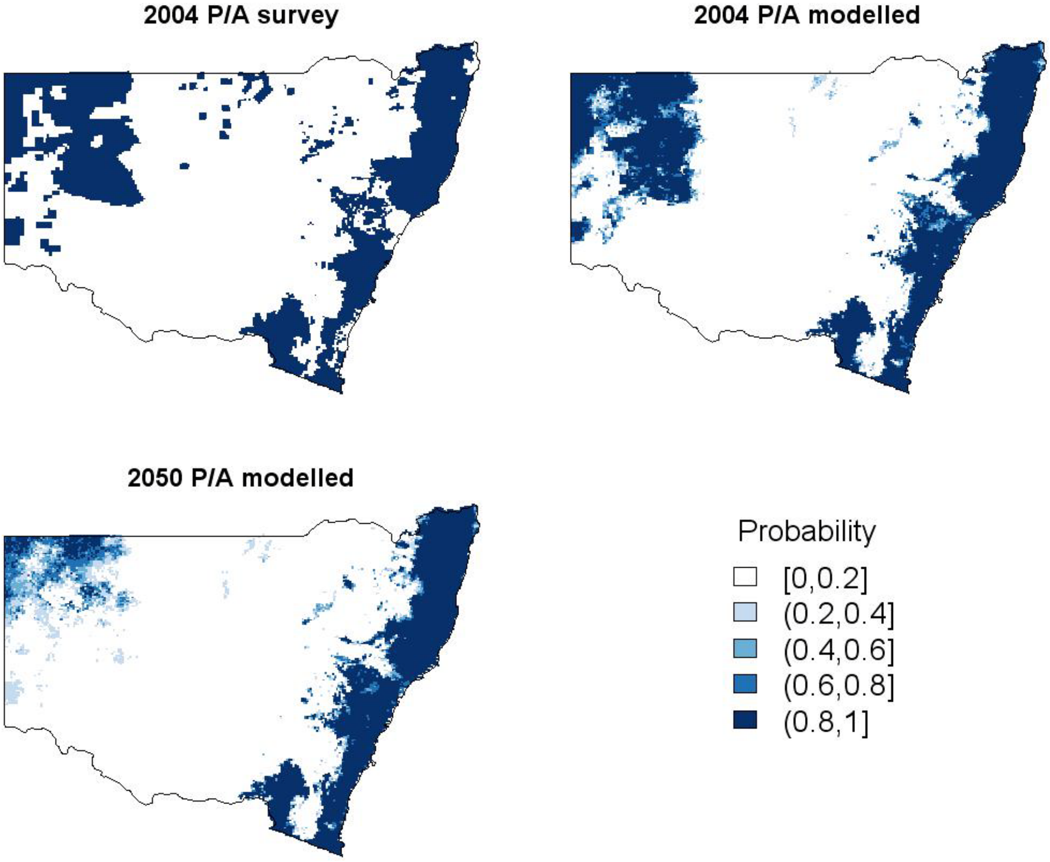
3.3.2 Wild dogs

Quantitative SDM predictions

As with feral cats, the SDM model underestimates the extent of habitat considered to contain high densities of wild dogs in 2004 (Map 8) though it performs very well in modelling the presence/absence of wild dogs (Map 9).



Map 8. For wild dogs, the observed density ('2004 Data'), modelled density ('2004 modelled'), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario ('CSIRO SRES A2A 2050' etc), and ensemble forecast from the four models for 2050 ('ENSEMBLE SRES A2A 2050').



Map 9. Observed, modelled and forecast presence/absence (P/A) data for wild dogs.

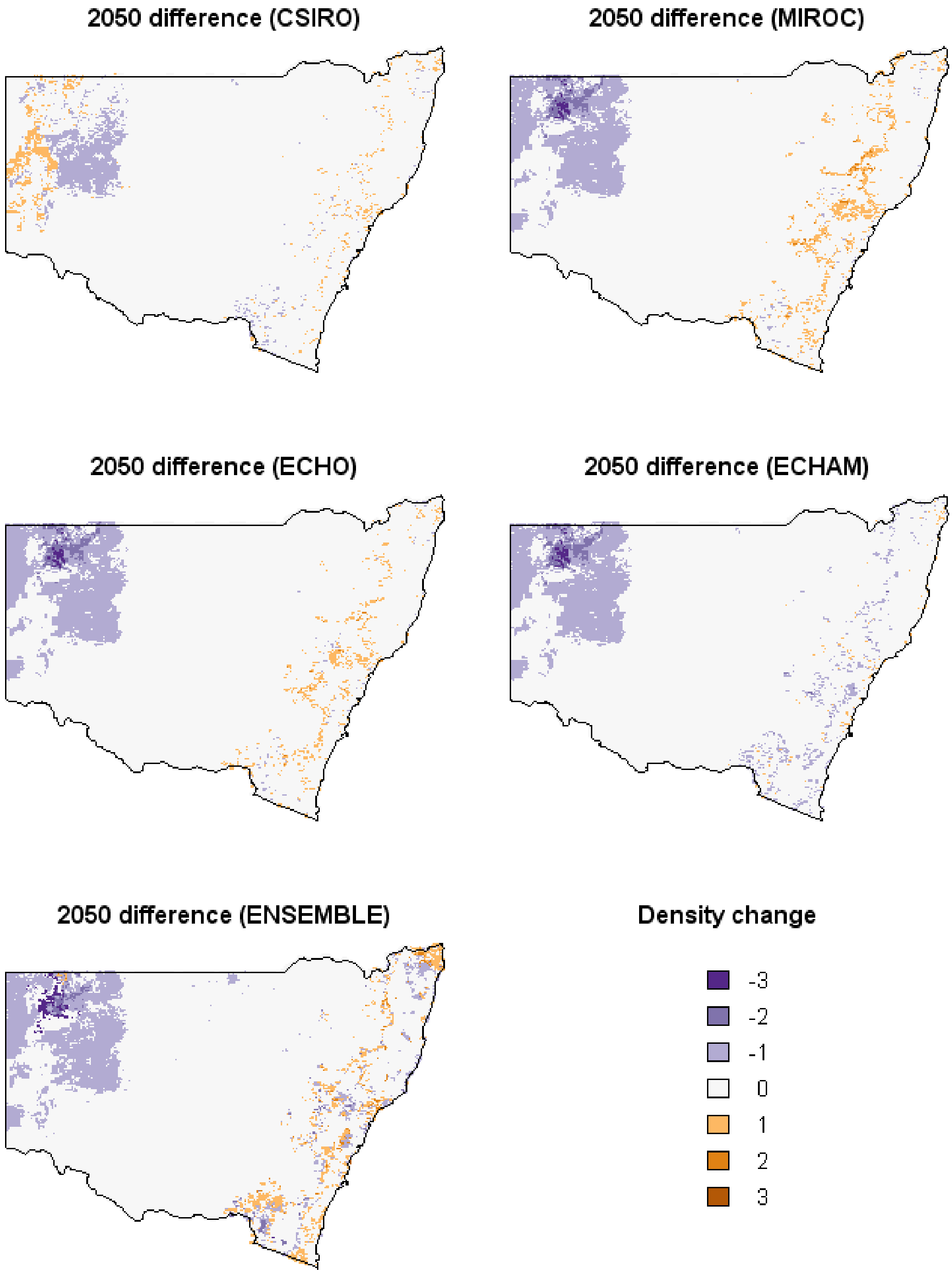
The ensemble 2050 predicts a decrease in the density of wild dogs in northwest NSW and a combination of increases and decreases along the Great Dividing Range (Table 9; Map 10).

Table 9. Changes in forecast density of wild dogs.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	0	0	0	0	0	0	0	na
1	80.9	87	86.8	98.3	97.4	92.4	11.5	14.2
2	17.5	12.4	12.9	1.7	2.6	7.4	-10.1	-57.7
3	1.6	0.6	0.2	0	0	0.2	-1.4	-87.5

Qualitative predictions

The current distribution of wild dogs is mainly determined by land use and associated management practices. In particular, sheep grazing and wild dogs are largely incompatible (Fleming et al 2001), hence areas where sheep are grazed are subject to highly active dog control programs. Cattle farming enterprises can tolerate some wild dogs, and there is uncertainty as to whether the moderate levels of control typically achieved by poisoning operations have any measurable effect on calving losses (Eldridge et al 2002, Allen and Fleming 2004).



Map 10. Differences between the 2004 survey density of wild dogs and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario.

Attitudes towards wild dogs are changing rapidly. These animals are argued to be a necessary component (a ‘keystone’ or ‘top-order’ predator) of a functioning nature conservation estate (Glen et al 2007). Whether wild dogs with reduced frequency of dingo genes function in the same manner as pure dingoes is open to speculation (Claridge and Hunt 2008). Where land use allows wild dogs to exist, their density is determined largely by the availability of preferred prey species (mainly macropods and rabbits) and access to permanent water.

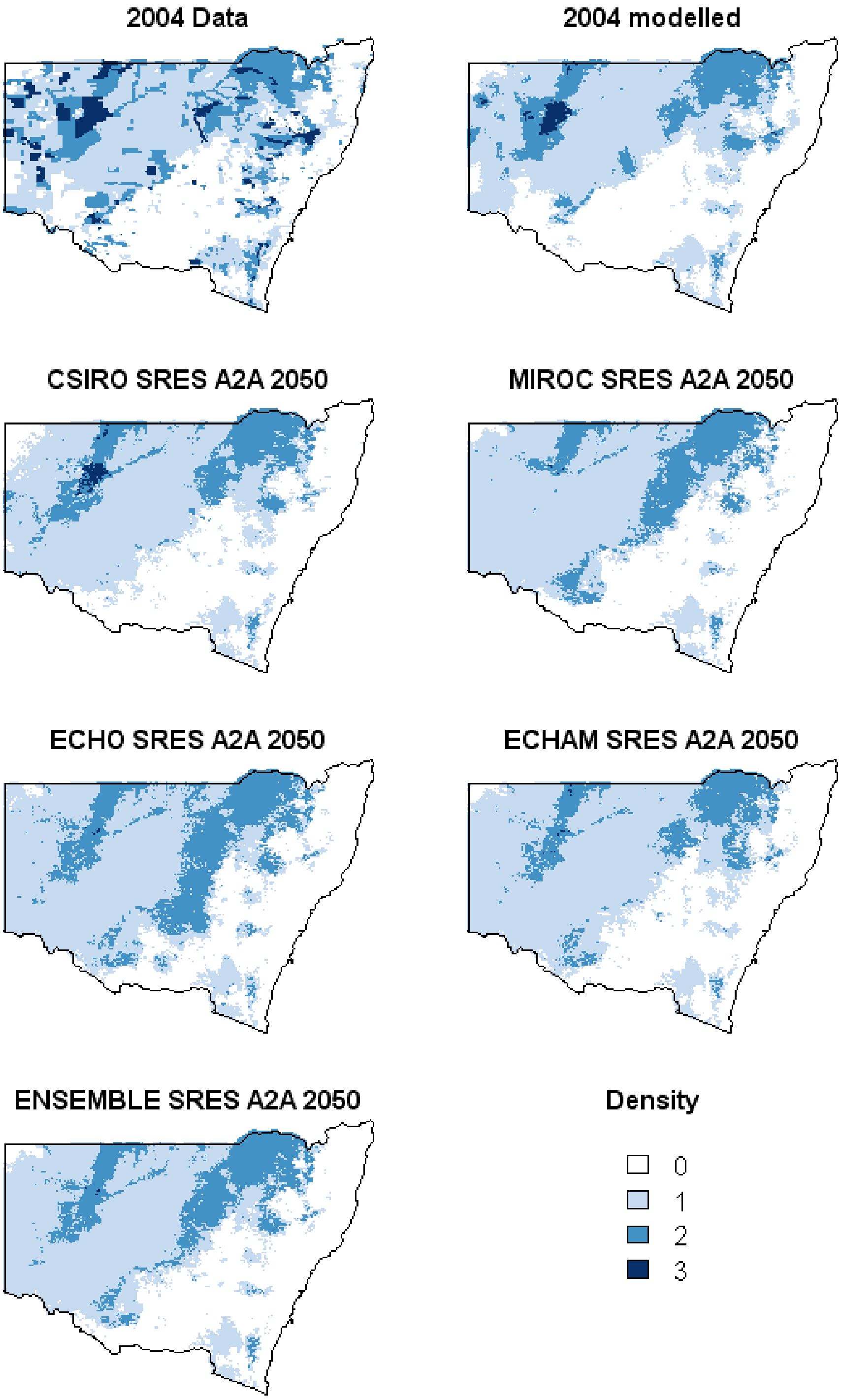
We predict that climate change will affect wild dog distribution indirectly through changes to the distribution and abundance of their prey base, which will alter because of direct climate effects and land use changes. These changes are expected to cause major increases in the distribution and abundance of wild dogs in NSW for several reasons.

The national sheep flock has dramatically reduced in size in recent years, and was 67.7 million at 30 June 2010 (the lowest level since 1905), down from 71.6 million at June 2009, 76.9 million at 30 June 2008 and 85.7 million at 30 June 2007 (Australian Bureau of Statistics 2009, 2010). The drop in numbers is due to more frequent drought conditions, generally low wool prices, and—at least anecdotally—the impact of wild dogs. The decline in sheep numbers is projected to stabilise in the short term and recover slowly, remaining low in historical terms in the medium term (ABARES 2011). Many graziers are, however, ‘getting out of sheep’ and either running cattle or ceasing livestock production altogether (Tony Peacock, personal communication). One effect of the recent decline in numbers will be to decrease the amount of pastoral land where landholders are seeking to actively control wild dogs. In areas where the nature conservation estate and/or forestry estate is expanding at the expense of unprofitable or marginally profitable grazing land, the withdrawal of domesticated livestock is typically followed by a dramatic increase in macropod numbers. This provides prey for wild dogs. For example, livestock were removed from the former Gudgenby Station by the early 1990s after it was incorporated into Namadgi National Park, ACT. By the mid-2000s the eastern grey kangaroo (*Macropus giganteus*) population had increased from a very low base, and in association, the development of a sizeable resident wild dog population (Fletcher 2006, Claridge et al 2009). Such increases will occur most rapidly in locations along or near the Great Dividing Range where wild dog distribution is more or less continuous and recolonisation is expected to be rapid. A recent example of changing land use leading to less coordinated wild dog control is in the Hunter Valley (Fitzgerald and Wilkinson 2009).

3.3.3 Feral pigs

Quantitative SDM predictions

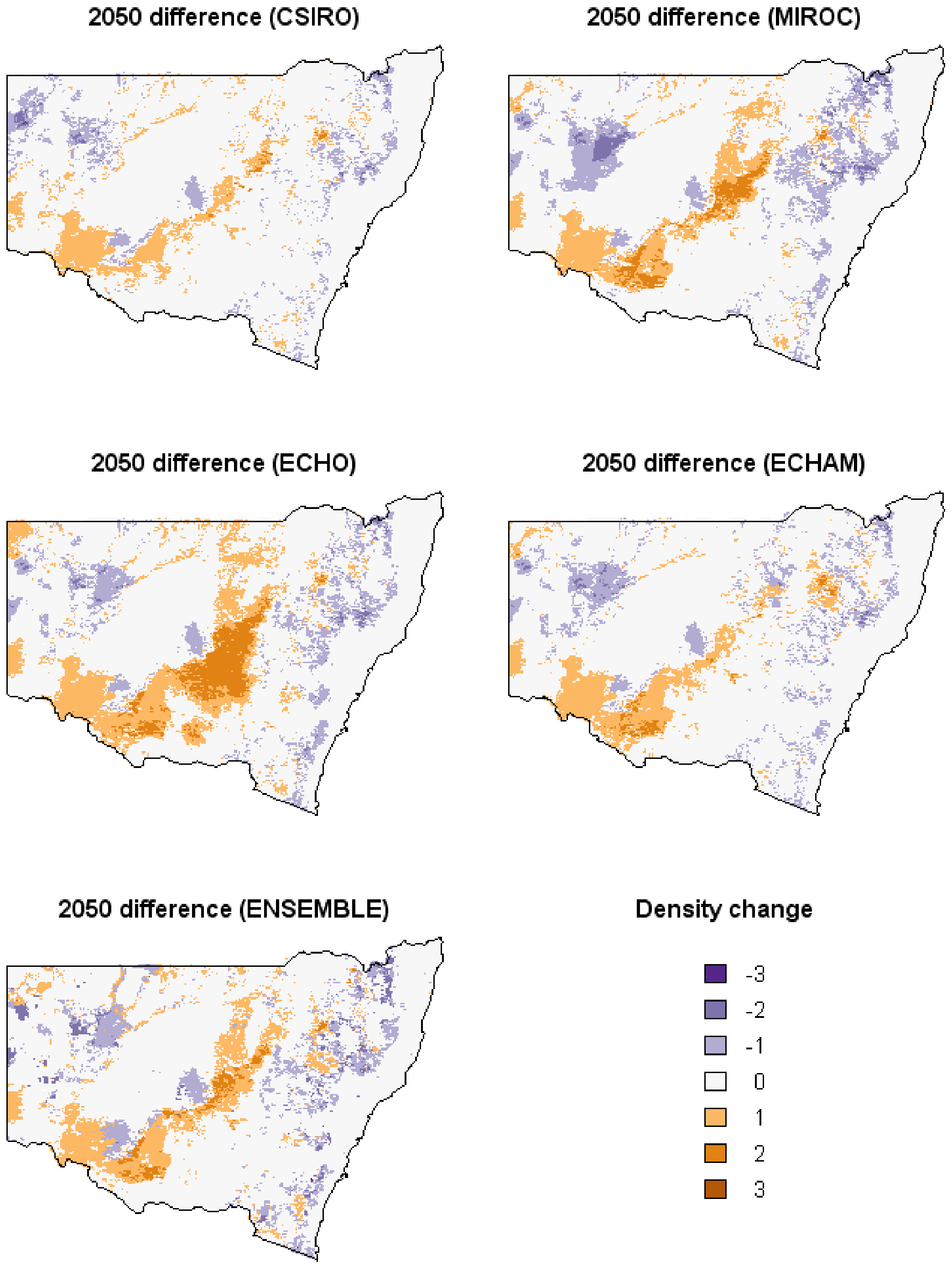
The SDM performs poorly in indentifying areas of high feral pig density, although it performs well in predicting feral pig distribution (Map 11). Under the 2050 climate forecasts, the SDM predicts an increase in the distribution of pigs across NSW, mostly in the low density category (Table 10), and mostly in a diagonal band east of the Darling River (Map 12).



Map 11. For feral pigs, the observed density (‘2004 Data’), modelled density (‘2004 modelled’), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario (‘CSIRO SRES A2A 2050’ etc), and ensemble forecast from the four models for 2050 (‘ENSEMBLE SRES A2A 2050’).

Table 10. Changes in forecast density of feral pigs.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	40.2	37.1	34.1	36.7	30.7	34.6	-5.6	-13.9
1	43.4	47.7	52.9	46.9	47.8	48.8	5.4	12.4
2	15.3	14.6	13	16.3	21.5	16.4	1.1	7.2
3	1.2	0.7	0.1	0	0.1	0.2	-1	-83.3



Map 12. Differences between the 2004 survey density of feral pigs and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario.

Qualitative predictions

To some extent, the current distribution of wild pigs reflects initial release sites. Wild pigs were still expanding their range in NSW in 2004 (West and Saunders 2007) despite dry conditions in the preceding years. This expansion confirms that they expand their range slowly (at about 2 km per year calculated by Caley (1997) and 4 km per year reported by Hone and Stone (1989)). As with their worldwide distribution (including wild boar), the distribution of wild pigs in NSW incorporates a wide variety of habitats and climates. The wild pig is a habitat generalist— in any given location the most pertinent question is not 'Why are pigs present?' but 'why aren't pigs present?'. They must have access to permanent water, and cannot cope with excessive winter snow (>about 50 cm) depth (Melis et al 2006). Winter harshness imposes density-independent mortality on wild boar populations (Melis et al 2006), but there are few areas in NSW that have such harsh winter conditions. At the opposite temperature extreme, they must have access to water and to thermal refuges such as riverine woodlands in extremely hot weather, and their distribution within a landscape appears limited by temperature interacting with thermal refuges (Choquenot and Dexter 1995, Dexter 2003). Artificial water is generally available in the pastoral lands of NSW.

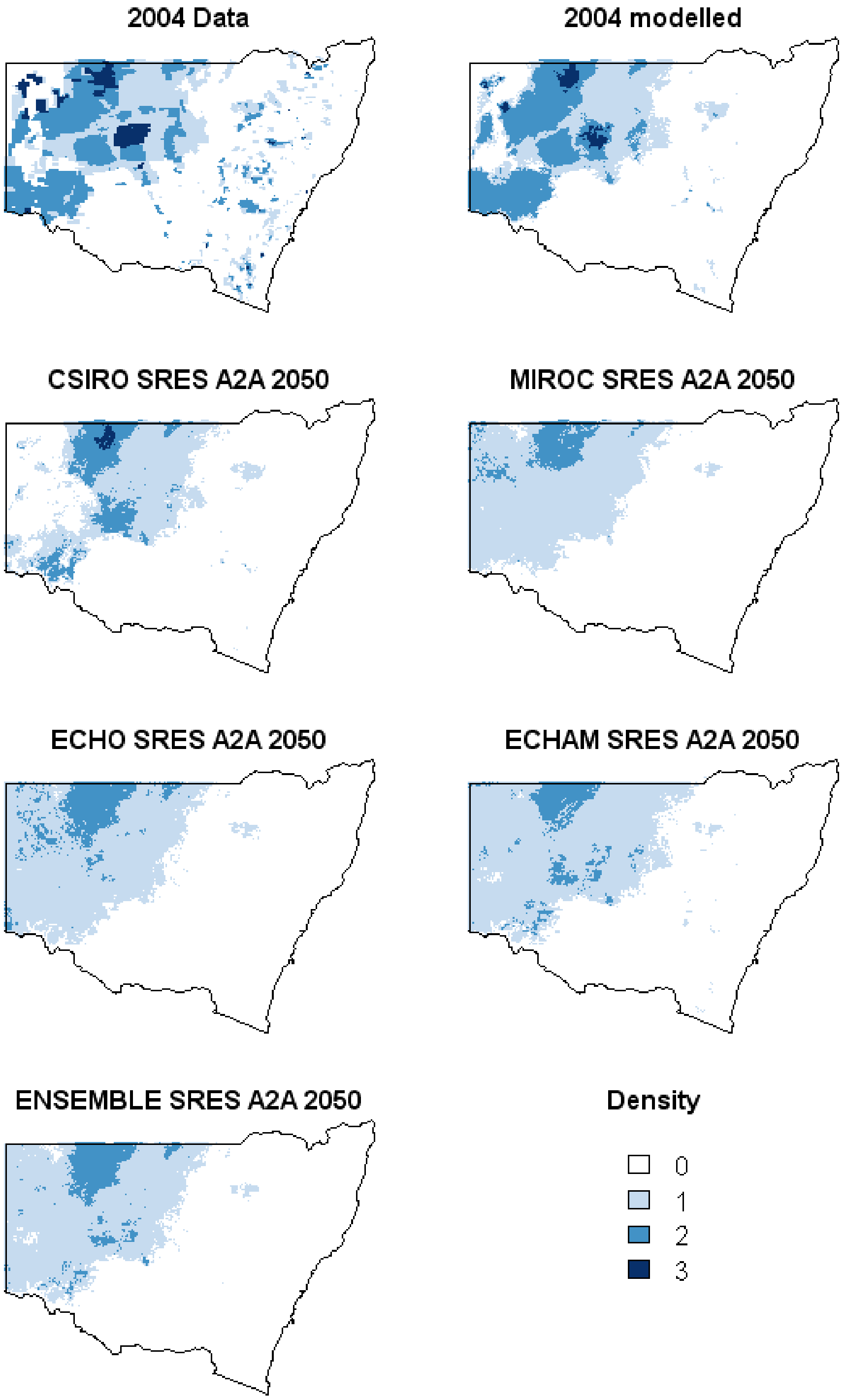
Increased areas of forest and other land set aside for purposes such as carbon sequestration will have a positive effect on wild pig distribution. Interspersing refuge habitat with food resources will improve landscape complementation, thus improving foraging efficiency and population growth rates of the pigs (Choquenot and Ruscoe 2003). The resulting greater connectivity of suitable habitat will probably help wild pigs to colonise new areas. At the same time that the environment becomes more favourable for pigs, changes in land tenure (eg increasing numbers of hobby farms) will make control operations over biologically meaningful areas more difficult to coordinate. The productive high rainfall coastal lowlands of north-eastern NSW (Clarence/Richmond River/Tweed basins) are highly suited to wild pigs, and these areas are expected to be colonised in time. Increased environmental flows to rivers and in particular wetlands (eg the former Macquarie Marshes where pigs were once abundant (Giles 1980)), will enable wild pig population numbers to increase in these areas. Conversely, increased temperatures in the interior would be expected to reduce the distribution of wild pigs in western areas where there is strong evidence to indicate they are already thermally limited—all the more so if surface water availability is also reduced. Further capping of free flowing bores ('bore drains') and better management of water troughs when paddocks don't have stock may decrease the ability of pigs to persist in semi-arid areas.

Control efforts by humans can keep wild pigs out of large areas if the efforts are sufficiently intense, or habitat fragmentation is sufficient to slow immigration. Control efforts can involve a degree of harassment (eg shooting from the ground and helicopter, hunting with dogs) or not (eg poisoning and trapping). The latter techniques, whilst capable of reducing abundance, rarely result in wild pig eradication even when applied for extended duration (eg Hone 2002), and hence don't change the distribution of pigs markedly. In contrast, if there is insufficient refuge habitat ongoing harassment techniques can locally eradicate wild pigs and prevent them from establishing in new areas. This type of control requires 'eyes' and 'ears' living on the land to promptly identify and respond to incursions by groups of wild pigs. Changes in land use that remove permanent human presence (eg conversion to forestry or conservation estate) will make it more likely that wild pigs can establish and persist in new areas. Indeed, the recent ongoing expansion of wild pig populations in NSW (West and Saunders 2007) may be evidence of this. Once a sufficient area of suitable habitat provides refuge and food, it becomes difficult to eradicate established wild pig populations or prevent new populations from establishing. The ability of wild pig populations to withstand intensive control pressure depends on the availability of refuge habitats (to escape control) and/or their maximum rate of increase in that habitat (to recover from control). In general, the status of pigs as a declared pest under state legislation has failed to stop their spread (Izac and O'Brien 1991). They have continued to expand their range within NSW (Hone and Waithman 1979, West and Saunders 2007) despite being declared noxious (meaning they must be eradicated by law) in all districts since 1955.

3.3.4 Feral goats

Quantitative SDM predictions

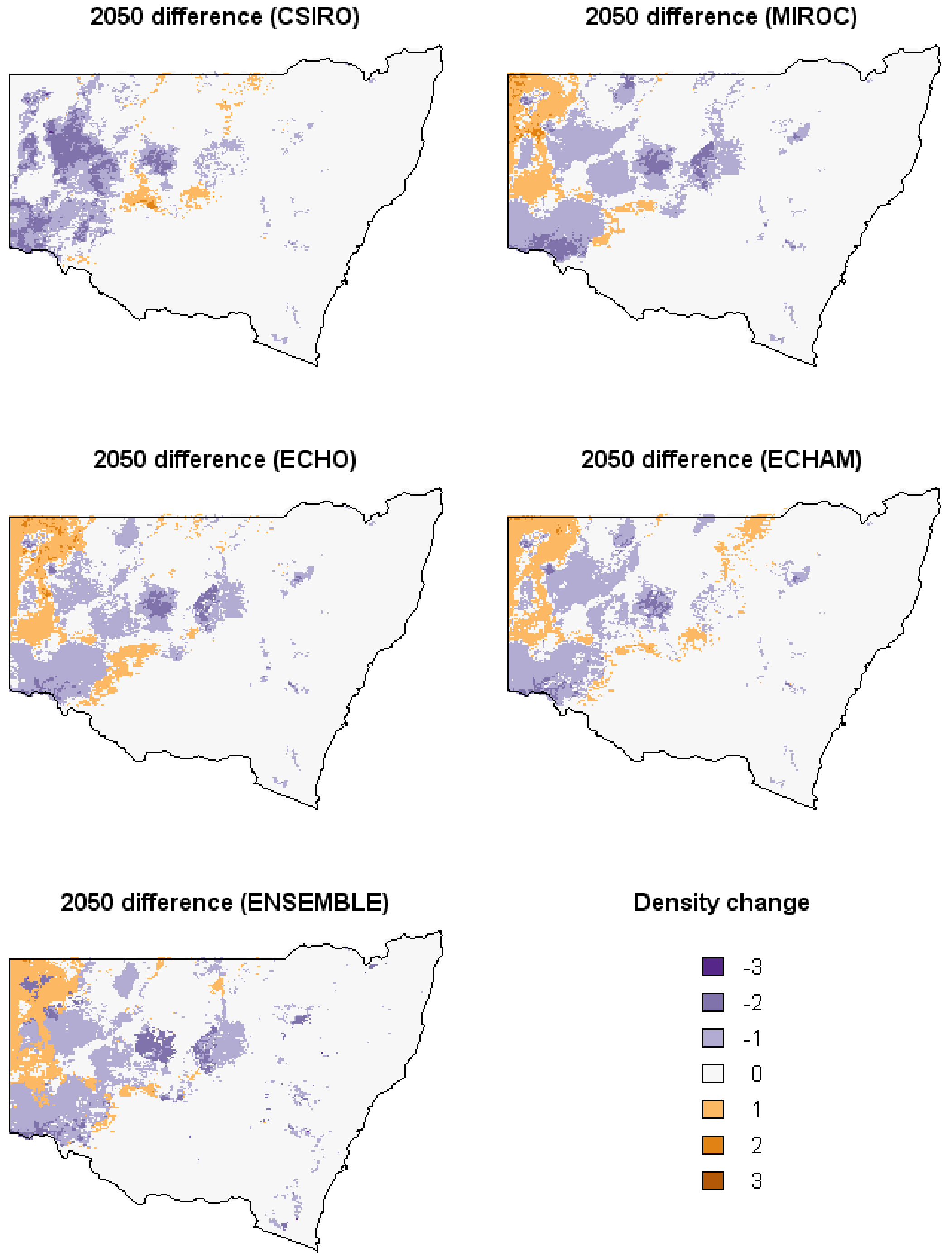
The SDM performed well in predicting goat density in western NSW, but performed poorly in identifying isolated goat populations scattered across the western slopes of the Great Dividing Range (Map 13). Under nearly all GCM projections, the distribution of feral goats is forecast to increase slightly, with all this increase occurring in the low density category at the expense of moderate and high densities (Table 11). All models except CSIRO predict a substantial increase in density in north-western NSW (Map 14).



Map 13. For feral goats, the observed density (‘2004 Data’), modelled density (‘2004 modelled’), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario (‘CSIRO SRES A2A 2050’ etc), and ensemble forecast from the four models for 2050 (‘ENSEMBLE SRES A2A 2050’).

Table 11. Changes in forecast density of feral goats.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	67.8	73.2	61.4	66.6	63.9	66.3	-1.5	-2.2
1	15.9	18.7	33.8	30.1	30.5	28.3	12.4	78
2	15.1	7.7	4.7	3.3	5.6	5.3	-9.8	-64.9
3	1.2	0.5	0	0	0	0.1	-1.1	-91.7



Map 14. Differences between the 2004 survey density of feral goats and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario.

Qualitative predictions

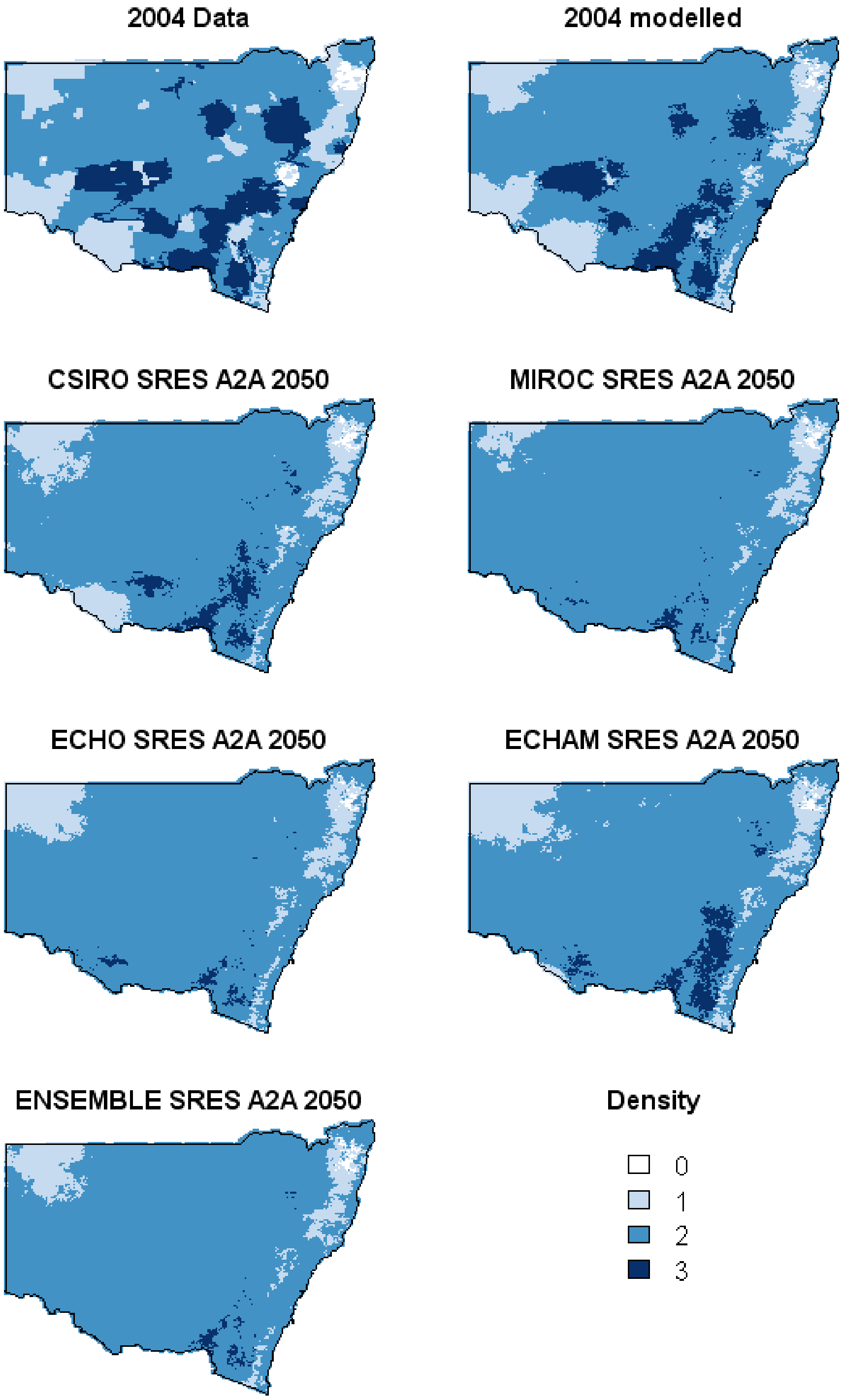
Goats are generalist herbivores. Like wild pigs, the biggest question relates to why feral goats are not present in an area. Predation by wild dogs and control by humans are the biggest influences on their distribution and abundance. In the absence of the refuge provided by rugged terrain, feral goat populations cannot persist in the presence of wild dogs. Indeed, Parkes et al (1996) note there are many examples where the presence of uncontrolled populations of wild dogs has restricted the distribution of feral goats, or where the removal of dingoes has allowed feral goats to colonise. They do also note exceptions to the ‘dingoes—no goats rule’, with reference to coexisting dingoes and goats in the Namadgi National Park (ACT), Ngarkat Conservation Park (southeastern South Australia) and localised areas in the Great Dividing Range. These exceptions do not withstand closer scrutiny. There are no longer goats coexisting with dingoes in Namadgi National Park, and Ngarkat Conservation Park has typically been subject to intensive wild dog control, making feral goat persistence there unremarkable. However, feral goats appear capable of coexisting with uncontrolled wild dog populations in rugged gorge country in NSW (eg Bayne et al 2000). In the absence of wild dogs, the persistence of feral goat populations is often facilitated by compliant landholder attitudes (Parkes et al 1996), where a population is maintained to be harvested if desired. Control of feral goats by mustering and/or commercial shooting typically does not locally eradicate goats, and may not even reduce density appreciably over large areas (Pickles 1992), as only high density feral goat populations are economic to muster, and populations are typically left to recover after mustering.

A decrease in the distribution of feral goats is predicted for two reasons. Firstly, higher predation rates are expected, because of the predicted increase in the distribution of wild dogs arising from land use changes documented above. Secondly, where wild dogs are not present, feral goat populations will be subject to increasing scrutiny for their negative impacts on biodiversity and their ability to reduce ecosystem carbon storage (eg Mills et al 2005). The current threat abatement plan for feral goats (DEWAR 2008) aims to stop unmanaged goats colonising new areas in Australia. Competition and habitat degradation by feral goats is listed as a key threatening process under NSW legislation (DECCW 2009b).

3.3.5 Foxes

Quantitative SDM predictions

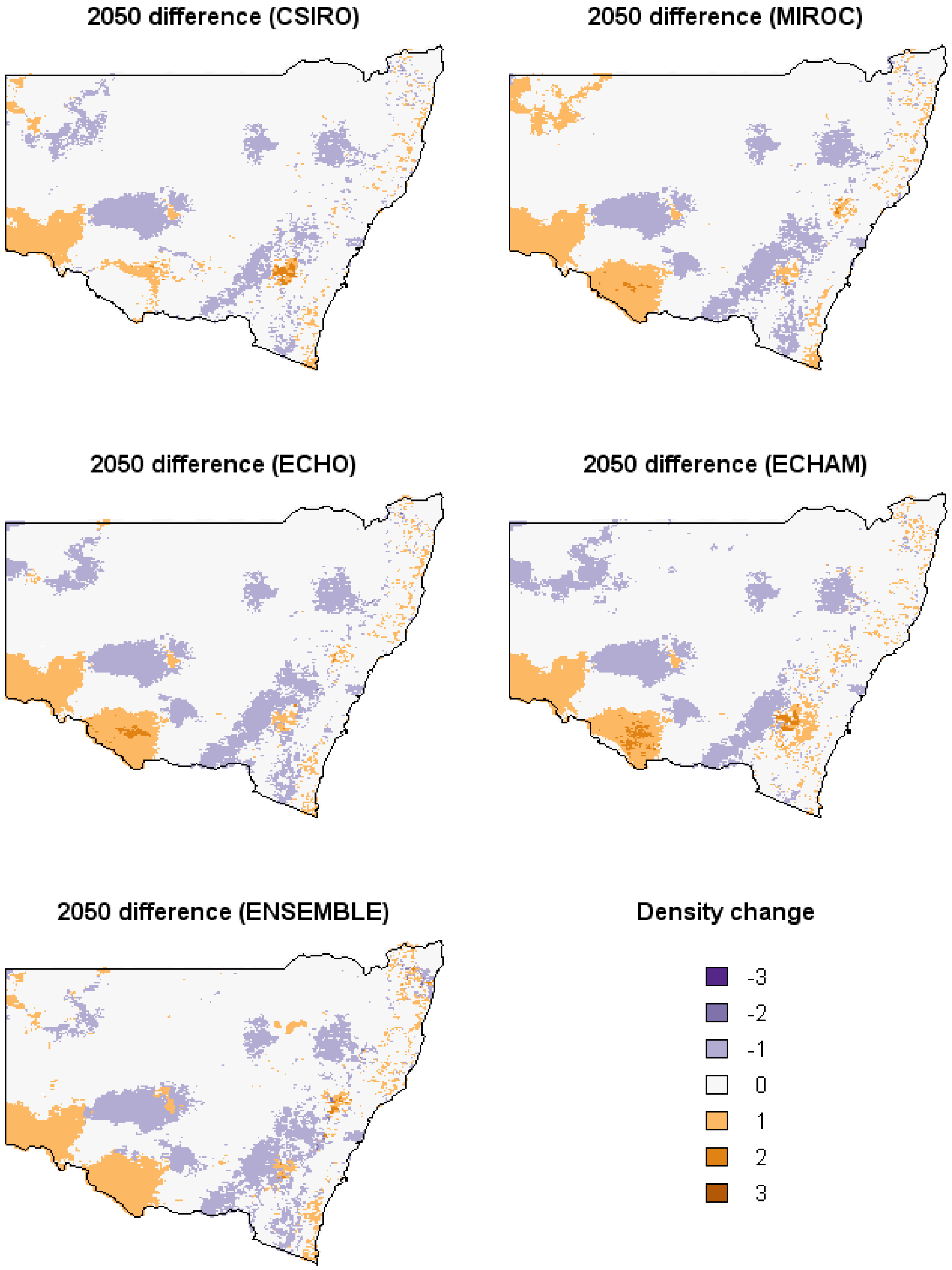
The SDM performs well in predicting 2004 fox density (Map 15) and predicts an increase in the area containing moderate fox density in 2050 at the expense of low and high fox density (Table 12). Major areas of increased density are predicted to occur in the south-west of NSW (Map 16).



Map 15. For foxes, the observed density (‘2004 Data’), modelled density (‘2004 modelled’), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario (‘CSIRO SRES A2A 2050’ etc), and ensemble forecast from the four models for 2050 (‘ENSEMBLE SRES A2A 2050’).

Table 12. Changes in forecast density of foxes.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	0.4	0.4	0.3	0.3	0.3	0.3	-0.1	-25
1	16.6	13.1	12.2	7.1	11	10.8	-5.8	-34.9
2	71.3	82.4	82.5	91.6	87.7	86	14.7	20.6
3	11.7	4	5	1	1	2.8	-8.9	-76.1



Map 16. Differences between the 2004 survey density of foxes and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario.

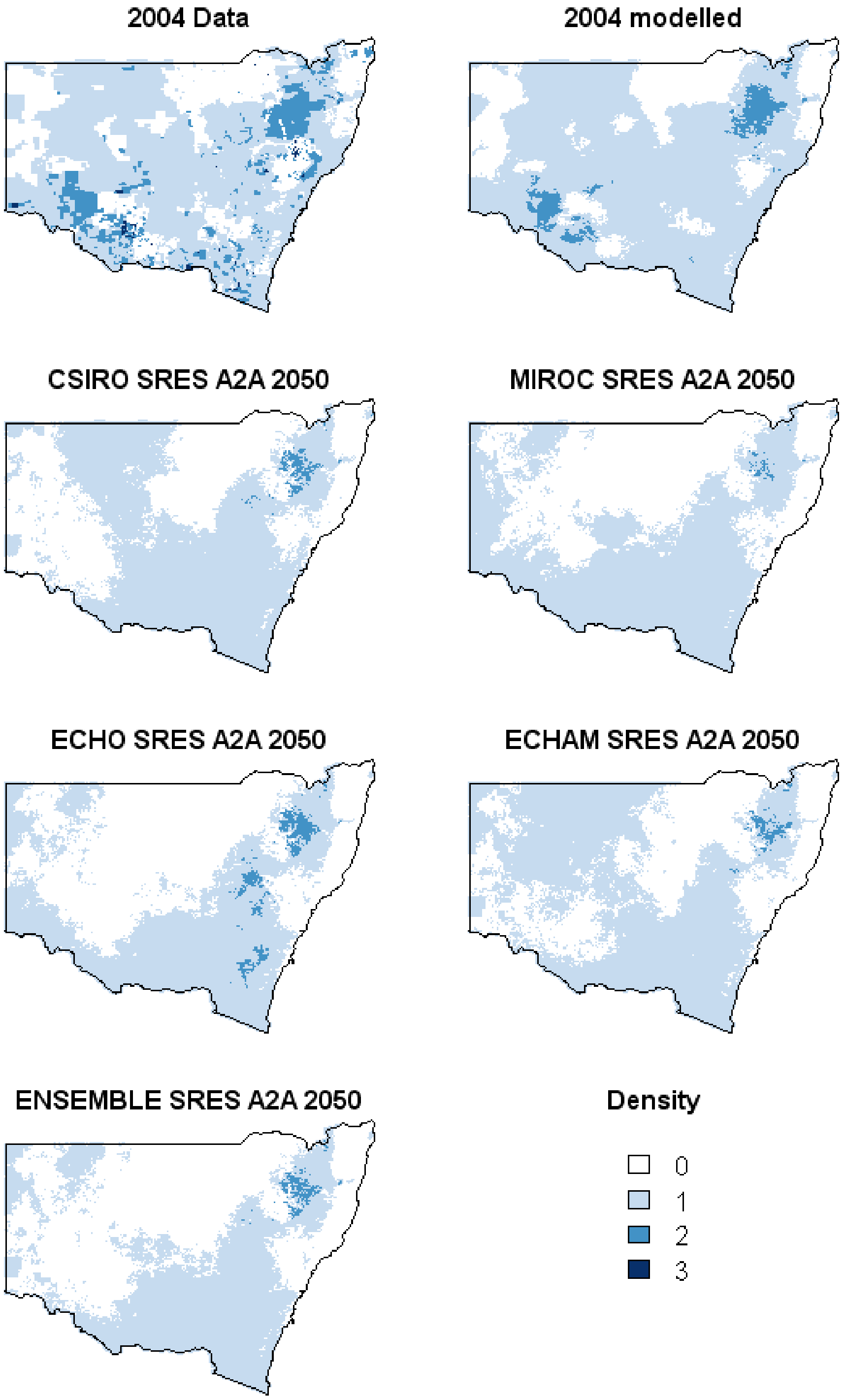
Qualitative predictions

The prediction of increased distribution and abundance of dingoes may have implications for foxes. Evidence on whether wild dogs exclude foxes is mixed (see Glen et al (2007) for a review) and quite polemical (eg Johnson et al 2007, Wallach et al 2009, Wallach and O'Neill 2009). On a landscape scale wild dogs don't fully exclude foxes (ie result in zero density), but they do directly prey on foxes (eg Marsack and Campbell 1990) and correlative data in some studies is consistent with them reducing fox density in some situations (Newsome et al 2001, Johnson and VanDerWal 2009, Letnic and Koch 2010). Evidence from North America supports temporal avoidance between grey foxes (*Urocyon cinereoargenteus)* and coyotes (*Canis latrans*) (Crooks and Soule 1999). So it is quite plausible that changes in the distribution and abundance of dingoes will have major effects on how foxes utilise the landscape. Note that a distinction needs to be made between 'stable' wild dog populations not subjected to control, and controlled wild dog populations, as it is postulated that stable wild dog packs with established territories are more likely to actively exclude foxes, and through cooperative hunting, be able to take larger prey items (Corbett 1995a). In summary, some changes are predicted in the way foxes spatially utilise the landscape where they occur, though little or no reduced overall distribution is predicted as a result of increasing wild dog distribution and abundance.

3.3.6 Rabbits

Quantitative SDM predictions

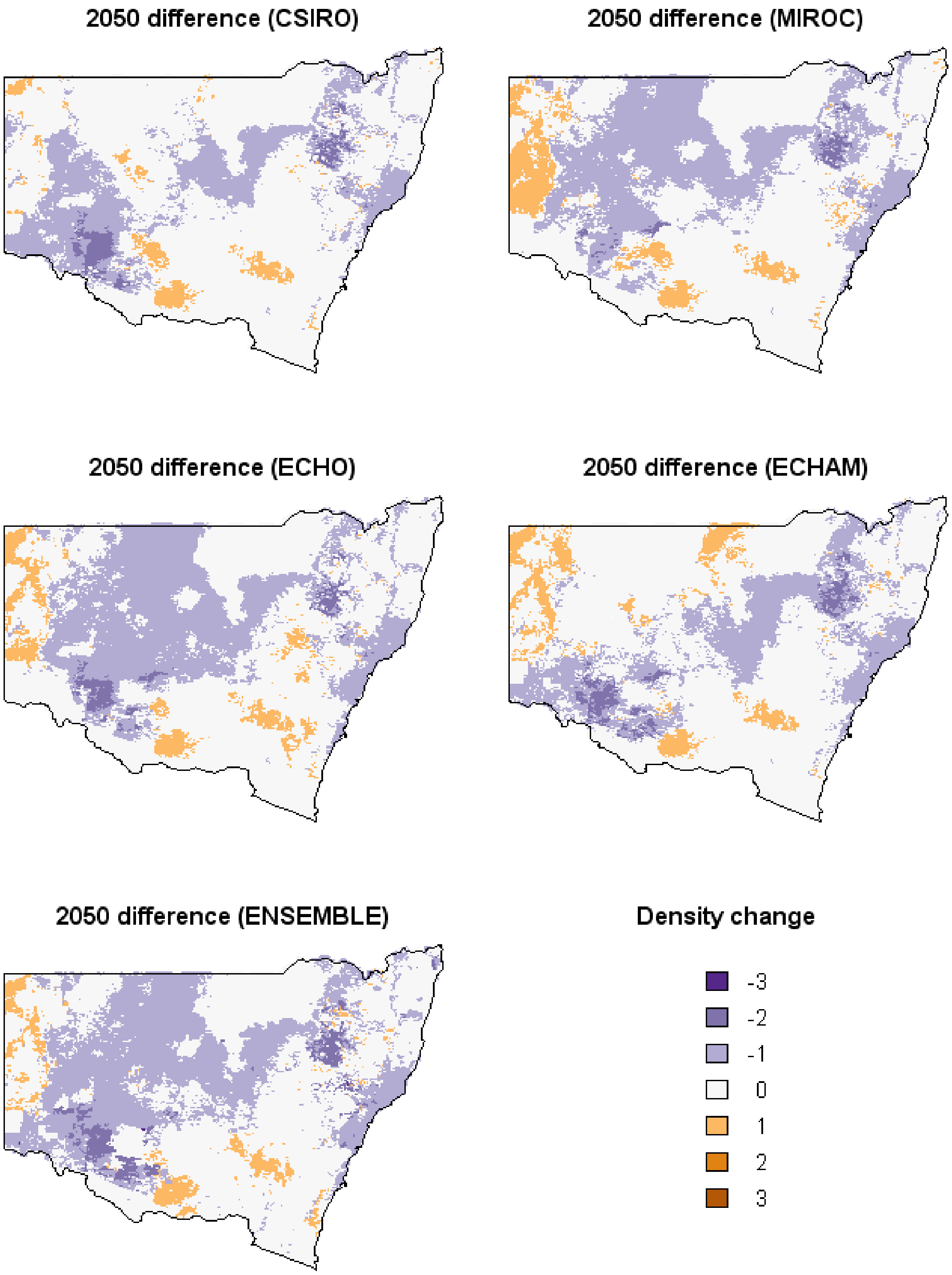
The SDM was successful in modelling the overall distribution of rabbits in 2004, but less successful at identifying isolated high density populations (Map 17). The general trend predicted under forecast climates was for a reduced distribution and generally reduced density (Table 13, Map 18). In fact, rabbits are predicted to become absent from substantial areas of central and western NSW. This prediction holds whether the climate gets hotter and drier (eg CSIRO GCM) or hotter and wetter (eg MIROC GCM).



Map 17. For rabbits, the observed density (‘2004 Data’), modelled density (‘2004 modelled’), forecast density in 2050 for the four GCMs assuming a medium–high emissions scenario (‘CSIRO SRES A2A 2050’ etc), and ensemble forecast from the four models for 2050 (‘ENSEMBLE SRES A2A 2050’).

Table 13. Changes in forecast density of rabbits.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)	relative change (%)
0	25	41.9	37.5	47.1	56	45.6	20.6	82.4
1	70.4	57	61.7	52.6	41.6	53.2	-17.2	-24.4
2	4.6	1.1	0.8	0.3	2.4	1.1	-3.5	-76.1



Map 18. Differences between the 2004 survey density of rabbits and the density forecast in 2050 under four different GCMs and their ensemble prediction, assuming a medium–high emissions scenario.

3.3.7 Cane toads

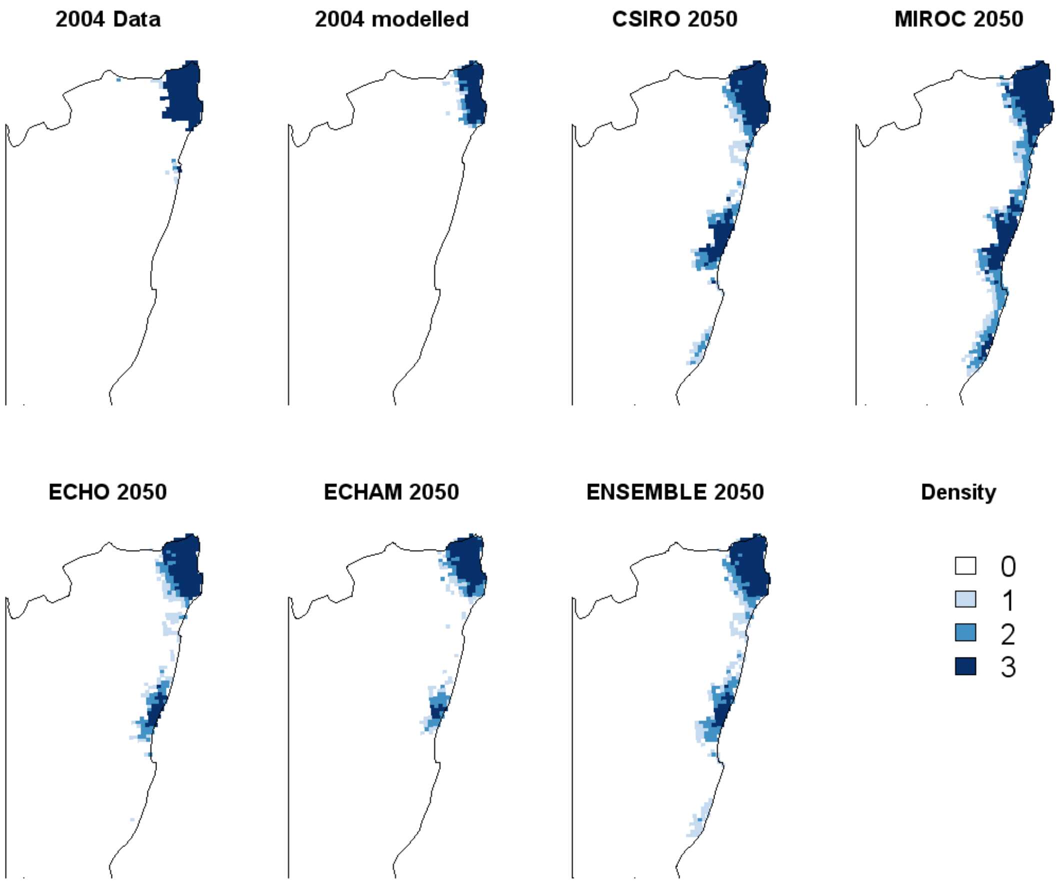
Quantitative SDM predictions

Unsurprisingly, the SDM predicted a major increase in cane toad distribution, from about 0.3% to 1.3% of NSW (Table 14). The increased distribution is predicted to remain largely restricted to coastal districts (Map 19, Map 20).

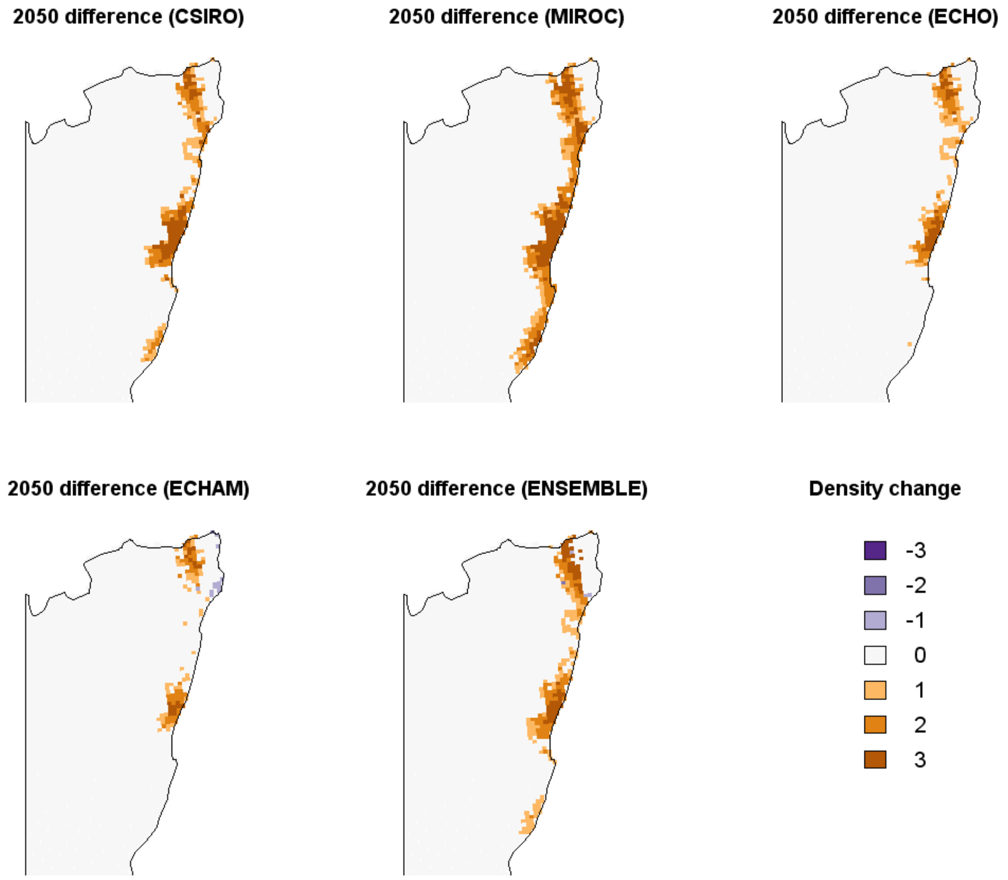
The predicted expansion is greatest for the MIROC GCM, which predicts a general increase in both temperature and rainfall for NSW.

Table 14. Changes in forecast density of toads.

density class	2004	CSIRO	ECHAM	MIROC	ECHO	ensemble	absolute change (%)
0	99.7	99	99.4	98.6	99.2	99	-0.7
1	0	0.3	0.2	0.3	0.2	0.2	0.2
2	0	0.2	0.1	0.4	0.1	0.2	0.2
3	0.2	0.5	0.3	0.6	0.4	0.4	0.2



Map 19. Observed, modelled (2004) and forecast density of cane toads by 2050 under a medium–high emissions scenario (SRES A2A).



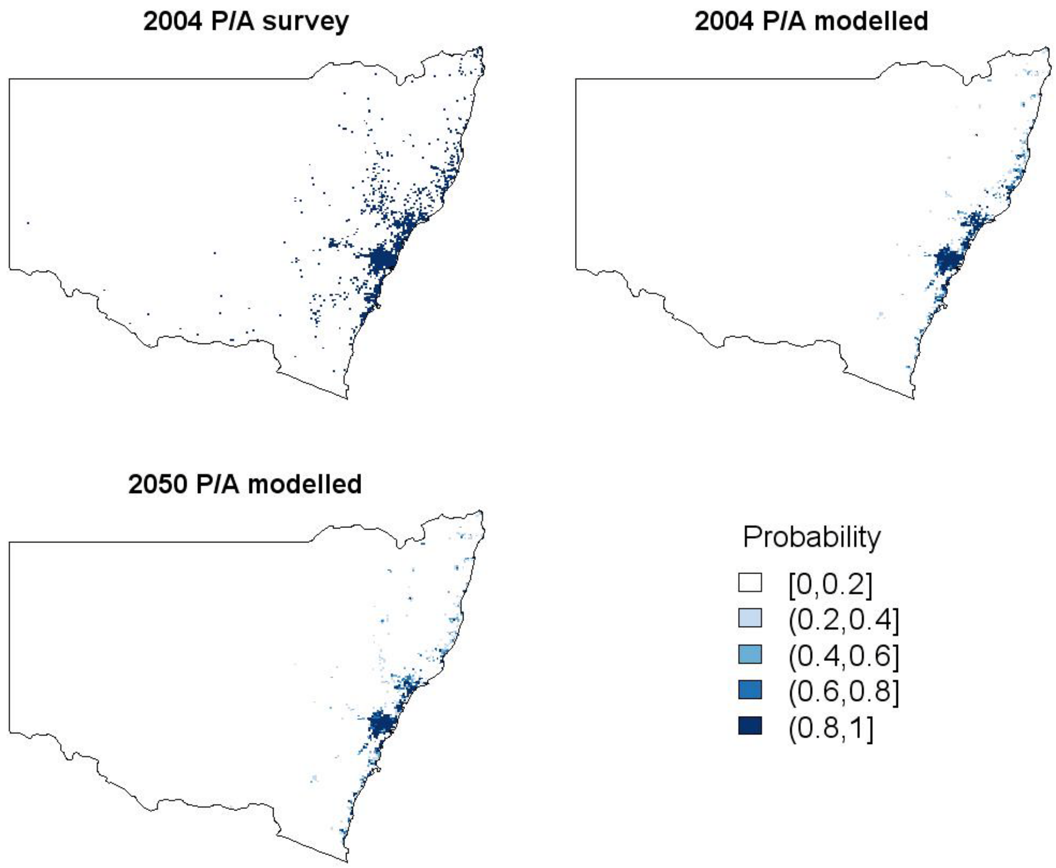
Map 20. Forecast changes in the predicted density of cane toads by 2050 under a medium–high emissions scenario.

3.3.8 Indian mynas

Quantitative SDM predictions

The SDM is largely uninformative for the Indian myna. The 2004 survey data shows a concentration of myna records throughout the Sydney basin extending north to the central coast and mid-north coast with a clear pattern of occurrence up through the Hunter on to the northern tablelands (Map 21). Their distribution is also evident along major transport routes out to parts of the central tablelands, southern highlands, ACT and south coast. Modelled 2004 occurrence concentrates distribution across greater Sydney, the central coast and parts of the mid-north coast and southern highlands. The 2050 predicted occurrence is similar to the 2004 model with less representation along the central and mid-north coast.

However, we do not believe the range contraction predicted by the 2050 model is likely to happen. Where not constrained by low temperature (Martin 1996), we expect this omnivorous species will continue to spread into rural and urban areas across parts of eastern NSW. We note the current distribution is consistent with predictions made more than 30 years ago of further incursions into coastal areas, the Hunter and the tablelands (Hone 1978). Peacock et al (2007) discuss the positive association between myna abundance and land modification in South Africa. While commonly regarded as commensal with humans, the species is nevertheless found in reserves and less disturbed environments in Australia and other parts of the world (Pell and Tidemann 1997, Peacock et al 2007). Increasing landscape modification and fragmentation of native vegetation for industry and urban settlement will help the Indian myna to increase its distribution across parts of eastern NSW.

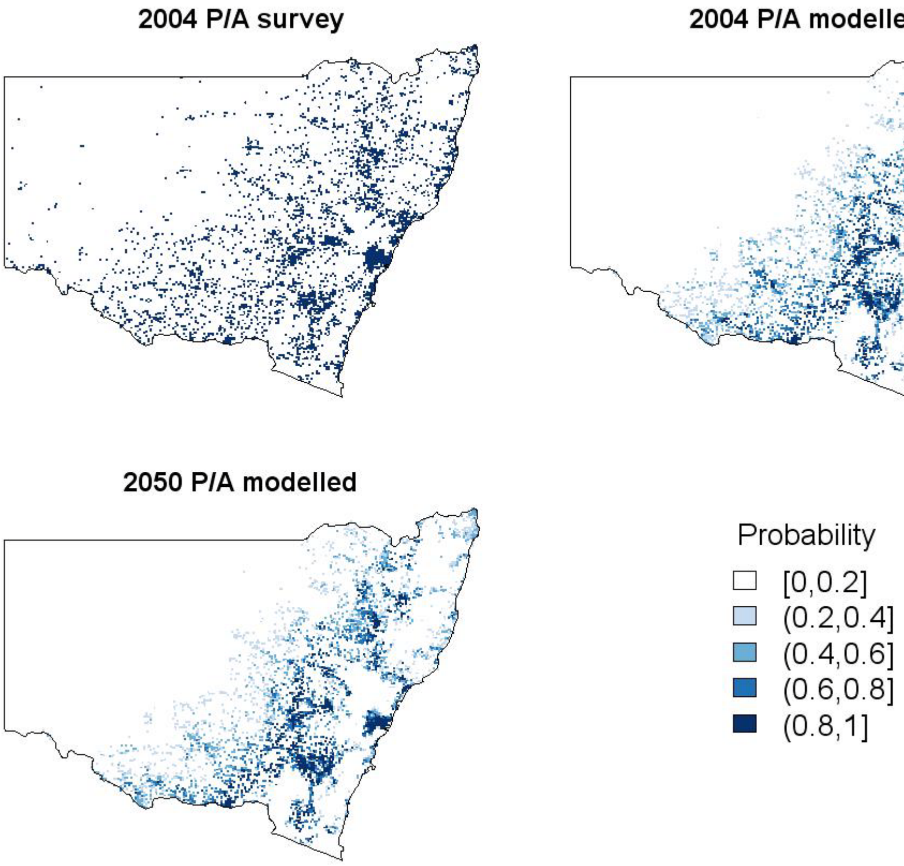


Map 21. Observed and modelled (2004) presence/absence (P/A) and forecast distribution of Indian myna by 2050 under a medium–high emissions scenario.

3.3.9 Starlings

Quantitative SDM predictions

The model performed poorly in predicting presences and absences of starlings (Table 6, Map 22), hence caution is advised in drawing conclusions from the results. Possible problems with the modelling approach are considered in the Discussion.



Map 22. Observed and modelled (2004) presence/absence (P/A) and forecast distribution of starling by 2050 under a medium–high emissions scenario.

3.3.10 Wild deer

Qualitative predictions

Quantitative predictions were not made for wild deer as they are believed to be far from having reached their equilibrium distribution. The current distribution of wild deer in NSW is more an artefact of locations of escape and liberation than climate and habitat suitability. Fallow (*Dama dama*), red (*Cervus elaphus*), rusa (*Cervus timorensis*), sambar (*Cervus unicolor*) and chital (*Axis axis*) deer have established wild populations in NSW. Amongst these, there is a species suitable for nearly all climates and habitats other than the arid interior. Fallow deer currently have the most widespread distribution in NSW, with established populations ranging from the NSW–Victorian border to the NSW–Queensland border. Populations of rusa deer are thriving in a diverse range of habitats, ranging from the NSW south coast and southern suburbs of Sydney to the western suburbs of Brisbane. Sambar deer are steadily expanding their range into southern NSW and the ACT from Victoria. Red deer, which probably are least tolerant of disturbance, are still finding their way to the temperate climates they prefer, with populations on the periphery of the NSW high country. In time, they can be expected to successfully colonise subalpine habitats, and utilise alpine habitats extensively during summer months.

With time, deer species will colonise most of NSW, particularly the pasture-forest interface. This will be a result of natural spread and deliberate releases, which will occur despite the best efforts of authorities, and which were estimated by Moriarty (2004) to account for 58% of herds. Points of liberation will undoubtedly include land bordering conservation estates or the estates themselves. The general observation is that wherever there are farmed deer there are often escaped deer, with deer farm escape/releases accounting for 35% of herds in Australia as of 2004 (Moriarty 2004) and 38% of recent populations in New Zealand (Fraser et al 2000). There appears to be no such thing as deer reliably 'contained behind wire'. The predicted changes to land use will be to their advantage, as they thrive in 'melded' landscapes (eg Hewison et al 2009). Climate change is expected to directly influence the distribution of individual deer species, but as there are species capable of surviving in nearly all climates, the overall distribution of deer *per se* will possibly be affected only slightly—they will be distributed over all but the arid interior and intensively developed agricultural land.

In the long term, interspecific competition, possibly to the point of exclusion, is likely to occur between deer species. For example, sika deer (*Cervus nippon*) are replacing red deer in parts of their historical range in the central North Island of New Zealand, with a competitive advantage in digesting fibrous forage (Fraser 1996). Similarly, rumination in sambar deer (considered a tropical species) is more efficient than in red deer (a temperate species), which may have evolved to enable them to break down low-quality tropical forages more effectively (Semiadi et al 1994). Fallow deer are particularly effective at interspecific competition (Focardi et al 2006). The exact outcome from this competitive interaction is difficult to predict, but the future ranges of the various deer species may look very different to what is seen currently.

Based on interactions between the dingo-sized coyote (*Canis latrans*) and deer species in North America (eg Stout 1982, Berger et al 2008) and the dhole (*Cuon alpinus*) in Eurasia (Andheria et al 2007), it appears possible that wild dogs may limit, and in some cases regulate the abundance of smaller deer species (eg fallow, chital, hog). There are anecdotal reports of wild dogs slowing chital deer population spread in central Queensland. In general, the ability of predators to regulate non-migratory prey populations may depend on the presence of other limiting factors (eg drought, culling, disease) that keep prey within the density range that can be regulated (Messier 1995) and the presence of alternative prey that maintains the predator population (Sinclair 1995). The effects of such limiting factors on the distribution of deer are not certain, but predation and hunting have the ability to strongly influence herbivore foraging behaviour (Benhaiem et al 2008), and may prevent deer from colonising areas considered marginal in the absence of predators between now and 2050. This is more likely to be the case where alternative prey species for wild dogs (eg rabbits, kangaroos, wombats) are abundant, though it depends largely on wild dog prey selection and their prey-switching behaviour. So, the future distribution and density of wild deer will probably be influenced by management decisions affecting the future distribution of wild dogs.

Sambar and rusa deer appear particularly tolerant of human disturbance and adept at inhabiting environments with patchy refugia. For example, rusa deer are currently well established in the leafy western suburbs of Brisbane and the Sutherland Shire south of Sydney, where they are commonly observed in people's backyards, and are able to handle the regular disturbance arising from foraging in such areas. Red and fallow deer may also live close to major urban centres where small woodlots provide cover (Fraser et al 2000). Managing deer is a complex exercise in managing people and what they think about deer. For example, more than half of the landholders in Queensland with deer on their properties who responded to a mail survey expressed a desire for the deer population to stay at current levels or increase (Finch and Baxter 2007). Within the same survey only a quarter of the respondents thought deer caused environmental damage, but Dolman and Waber (2008) document many instances of introduced deer causing major disturbance to local ecosystems where they have reached high abundance, although none of the cited instances came from Australia. In truth, there is very little, if any, published work on the biodiversity impacts of introduced deer in Australia, other than documentation that they browse species considered endangered (Moriarty 2005). In assessing any prediction that their impact will be novel because they are a browsing species needs to consider the former possible effects on Australia's vegetation of browsing by at least six species of short-nosed kangaroo (Johnson 2006). This is in contrast to the impact of deer in New Zealand forest ecosystems, where the vegetation is considered relatively 'naïve' to ruminant herbivory (Nugent et al 2001). That said, it may well be that the impact of deer in NSW will be density-dependent, and that some form of control or predation will be needed to stop their densities becoming a threatening process to biodiversity.

The population growth rate of deer, and especially the smaller species, is such that a high level of population would need to be removed before this exerted any control over population size. For example, the finite rate of increase for suburban white-tailed deer (*Odocoileus virginianus*) from a site in the United States was 1.78 a year (Nielsen et al 1997). This would require annual removal of more than 40% to exert control over the population (Hone 2007, Fig. 3.7, p52). Nugent and Choquenot (2004) note that in New Zealand neither commercial nor recreational hunting is likely to be a cost-effective alternative to government-funded control where very low deer densities are required to achieve conservation goals in inaccessible or difficult-to-hunt areas. The chances of a government-sponsored control program achieving high levels of control over any sizeable area are slim (eg Caughley 1983). Controlling deer in forested areas is especially problematical. The propensity for certain individuals to translocate deer into new areas makes containment an unsustainable strategy, given the ongoing cost of eradicating new populations. History and current trends strongly suggest that future management efforts will achieve little in slowing their spread.

In summary, the existing wild deer species in NSW will progressively colonise nearly the entire state, other than the arid interior (especially if the 'hot & dry' GCMs prove correct). The final distribution of deer species will be largely determined by the interactions between the deer themselves and land use, rather than any effects of management.

4. Discussion

4.1 General trends in vertebrate pest distribution and impacts

This research was motivated by a concern that vertebrate pest species may expand their ranges under anthropogenically induced climate change. However, there was no consistent trend for the ranges of vertebrate pest species considered in this study to either expand or contract as a direct result of forecast climate change. Among the vertebrate pest species of most concern (feral goat, feral cat, fox, rabbit and feral pig), only the feral pig is predicted to increase its range substantially. The results predict that land use change, arising from a changed climate and climate mitigation measures (eg increased forestry) as well as from external forces (eg higher input costs which make more land areas marginal) will impact on the distribution of some vertebrate pests, particularly feral pigs, wild deer and wild dogs.

4.2 Climate scenarios

The climate scenarios forecast by the various GCMs differ substantially, particularly for rainfall. However, the forecasts of GCMs are in agreement that temperatures will continue to rise (by about 2^0 C by 2050 under an A2a (medium–high) emission scenario). Rising temperatures, greatly exacerbate the severity of droughts arising from rainfall deficiency (Ummenhofer et al 2009). The increased annual rainfall that is forecast may do little to change rainfall deficiencies. This is because greater annual rainfall may commonly result from increases in the intensity of a small proportion of rainfall events rather than an increase in events (rain-days) themselves (Taschetto and England 2009). Hence regardless of the GCM forecast used, droughts will continue, and their severity is likely to increase because of rising temperatures.

4.3 Land use changes

The forecast increase in the distribution of land use classified as suitable for low intensity grazing (at the expense of areas suitable for improved pasture) has implications for the viability of the Western Division, where most of the change in NSW is predicted to occur. There has long been concern that enterprises in the area are not economically viable (eg Davies 1985, Shepherd and Caughley 1987), and if people leave the land because farming is not viable, there will probably be changes in the distribution of pests such as wild pigs and wild dogs.

More generally, changes in land use (some as a result of climate change) will influence the distribution of vertebrate pests substantially, probably more so than direct biophysical effects of climate on the pests themselves. Economic responses of landholders will drive this change in ways which are not predictable using purely biophysical models. The imminent imposition of pricing on CO_2 emissions will probably provide landholders with an economic option of using their land for climate change mitigation. Land managers will choose among mitigation options depending on the nature of their land, the price and availability of water, carbon prices, and the development of new markets (for example, for biofuels) (Garnaut 2008). The proximity to markets and commodity and input prices will also determine patterns of production, possibly leading to expansions and/or contractions in livestock and cropping enterprises (Garnaut 2008).

4.4 Threat to native species

Climate change is expected to have deleterious effects on some native species and plant communities (Howden et al 2002, Taylor and Figgis 2007). Distributional changes and declines in abundance of native species may result from changes in community structure, productivity, foliage quality, and fire frequency and intensity. In some regions there will be increased risk of landscape degradation and sensitivity to disturbance. Reductions in snow cover are likely to result in weed and pest incursion. With these changes, the extent of habitat and refugia for native fauna will contract.

Existing threats to biodiversity including weeds, frequent fires and predation from vertebrate pests, are expected to intensify with the effects of climate change (Thomas et al 2004). One species, the wallum froglet (*Crinia tinnula*) inhabits low-nutrient coastal swamps and is listed as a 'vulnerable' threatened species under NSW legislation. Existing threats to the species include inappropriate fire regimes and habitat destruction from wild pigs (Meyer et al 2006) and predation from cane toads. These threats stand to be compounded with climate change due to expected expansion/increases in toad and wild pig distribution/abundance and greater risk of frequent fire.

Other native fauna species also illustrate the deleterious indirect effects that climate change is likely to have on threatened species, including the nationally and state (NSW, Victoria) listed 'endangered' mountain pygmy-possum (*Burramys parvus*) and the 'vulnerable' (NSW) broad-toothed rat (*Mastacomys fuscus*). Both species occur in alpine and subalpine habitats. Extent, depth and duration of snow cover is an important ecological factor for these species. The effect of climate change on reducing snow cover can have ramifications that are not immediately apparent, over and above simply increasing exposure to predation from foxes and wild cats (McDougall and Broome 2007). With reduction in snow cover accompanied by increases in fire frequency, primary habitat for the mountain pygmy-possum can be destroyed by the failure of mountain plum pine (*Podocarpus lawrencei*) to reach reproductive maturity. Early emergence from hibernation has been associated with early snow-thaw before the arrival of bogong moths, a key food resource of the mountain pygmy-possum. In alpine environments, the broad-toothed rat also relies on adequate snow cover for insulation, foraging and protection from predation (Green 2002, Green and Sanecki 2006).

These examples illustrate that the effects of climate change can be multi-faceted for threatened native fauna. An increased threat from changes in vertebrate pest distribution and abundance is rarely the whole story. With the endangered mountain pygmy-possum, climate change is expected to reduce habitat, shelter and food resources. Where fox and wild cat density remains unchanged, this reduction in resources will place the mountain pygmy-possum at a greater risk of predation from these two pests. Any increase in fox and wild cat abundance would be expected to amplify the threat to the species.

Similar deleterious impacts on native flora from complex interactions between exotic herbivores and omnivores (rabbits, goats, pigs) and the effects of climate change would be expected (Hughes 2003).

4.5 Changes affecting pest control

It is beyond the scope of this report to address in detail changes in human ecology surrounding vertebrate pest management and how such changes may influence control programs and hence pest distribution. However, a few comments are salient. Public attitudes towards introduced species will continue to change (eg Stromberg et al 2009), and will soften from the current predominant ‘hard line’ view (eg see Brown and Sax (2004)).There is evidence that attitudes towards introduced species such as cane toads do change with time. For example, Clarke et al (2009) report a trend whereby attitudes towards cane toads become more accepting as their residence time in a location increases. In addition to people becoming more accepting of introduced species (or resigned to their presence), the methods used for vertebrate pest control will be increasingly scrutinised to ensure that animal welfare and ethical requirements are met (eg Littin et al 2004). The end result may well be a general public more accepting of introduced vertebrates, and less likely to support control operations without clear justification. Broadening indifference to well-established pest populations may not occur across the board. In some situations an understanding of the destructive nature of vertebrate pests and a willingness to act in some communities will lead to support (and indeed initiation), of pest control programs. For example, cane toads and Indian mynas have been (and are) the focus of such community-orientated programs in NSW. Consistency, motivation and the need for expanding spatial coverage will determine to a large degree whether these community-centred programs will be effective in reducing pest impact.

Diversification of land use and land ownership will make coordination of control programs more difficult for mobile pest species whose home ranges traverse property boundaries. In the decades to come, a carbon-constrained economy may well exercise limitations on the ability to conduct vertebrate pest control programs, as these tend to be energy-intensive activities. For example, direct control methods such as shooting from helicopters (eg Choquenot et al 1999), aerial bait distribution (Fleming et al 2000), checking traps (usually daily to meet animal welfare requirements) and/or laying poison baits by vehicle, have substantial fuel costs. The price of oil is forecast to rise considerably over coming decades as the world moves from a demand-led to supply-constrained market (Owen et al 2010), and vertebrate pest control costs will rise commensurately. This increase in costs will disproportionately affect the already marginal viability of the extensive low input–output grazing systems of the rangelands, except where competitive interactions—such as between dingoes and feral goats—limit the impacts of some pests.

Whilst new toxicants and better delivery systems will undoubtedly be developed, the efficacy of the current generation of toxicants will inevitably decrease in populations that are continually subject to their use (eg Twigg et al 2002). The development of pesticide resistance is the norm, and given enough generations even highly susceptible populations of wild dogs should be expected to start developing resistance to sodium monofluoroacetate (compound ‘1080’), or become bait averse, or both. Certainly, effective bait-delivery methods are critical—there is evidence of wild dog populations persisting inside the dingo barrier fence in the presence of 1080 poisoning programs in areas such as the northern Flinders Ranges in South Australia (Pople et al 2000, Wallach et al 2009). Efforts to control wild dog populations inside the dingo barrier fence by poisoning are also hampered by the increased prey abundance in such locations (Allen and Sparkes 2001).

These changes affecting vertebrate pest control may require that benefit-cost analyses of standard vertebrate pest control methods are revised.

4.6 Pest data issues

There are limitations to the gridded data used in this report in both the pest density estimates and biophysical explanatory variables. The 5 x 5 km scale is reasonably coarse, and averaging explanatory variables over such a large area may produce a result that is not representative of the part of the cell where the pests occur.

There is a clear need for more extensive validation of the survey data used in this report. For example, the ‘wild dogs’ recorded at high densities throughout metropolitan Sydney are unlikely to be functionally the same as ‘wild dogs’ that refer to dingoes and dingo-like wild canids occurring elsewhere in NSW.

4.7 Species distribution modelling issues

There are dangers of predicting outside the data to which the models were fitted (Phillips et al 2008). Fitting correlative models with a large number of potential explanatory variables also has perils. From the many variables available, some may be included in the model although they represent spurious relationships with the response variable which do not generalise outside the current data set (Beale et al 2008, Mundry and Nunn 2009). These predictions must therefore be treated with caution, and evaluated in the light of ongoing monitoring data on the distribution and abundance of the species concerned.

The SDM modelling approach taken here assumes that species distributions were effectively at equilibrium. In fact distributions of some species may lag behind the niche they will occupy in future. Cane toads are probably an exception, because the speed of their invasion front probably greatly exceeds the rate at which climate change is making new areas environmentally suitable, and they have occupied the northern part of NSW for several decades.

4.8 Results of note for individual species

The prediction for feral pigs to expand their range in the western slopes is somewhat counterintuitive, as one would expect that a hotter and drier climate would be detrimental to feral pig populations. A reasonable explanation, however, is that a hotter and drier climate results in less intensive land use, which in turn is more conducive to feral pig occurrence, as seen in western NSW where some of the least productive habitats used for pastoralism have the highest recorded feral pig population density.

The trajectory of feral goat distribution is unclear—the SDM predicts an increase, but the expectation of expanded wild dog populations should result in a decrease.

As expected, cane toads are predicted to expand their range considerably under a forecast warmer climate. The training dataset for toads was very small, especially after subsets of the data were selected to obtain independence between observations. Using a larger training set (eg including data from southern Queensland) would be expected to improve the species distribution model for toads.

The modelling approach taken was unable to produce a useful model of the distribution or abundance of starlings and to a lesser extent Indian mynas. The bird survey techniques were systematic within sites surveyed, although the site selection process is not clear due to the nature of the survey program. Indeed, records are influenced by ease of access and remoteness. Possibly these data could be modelled more productively using a different approach that accounts for survey effort.

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7. Appendix

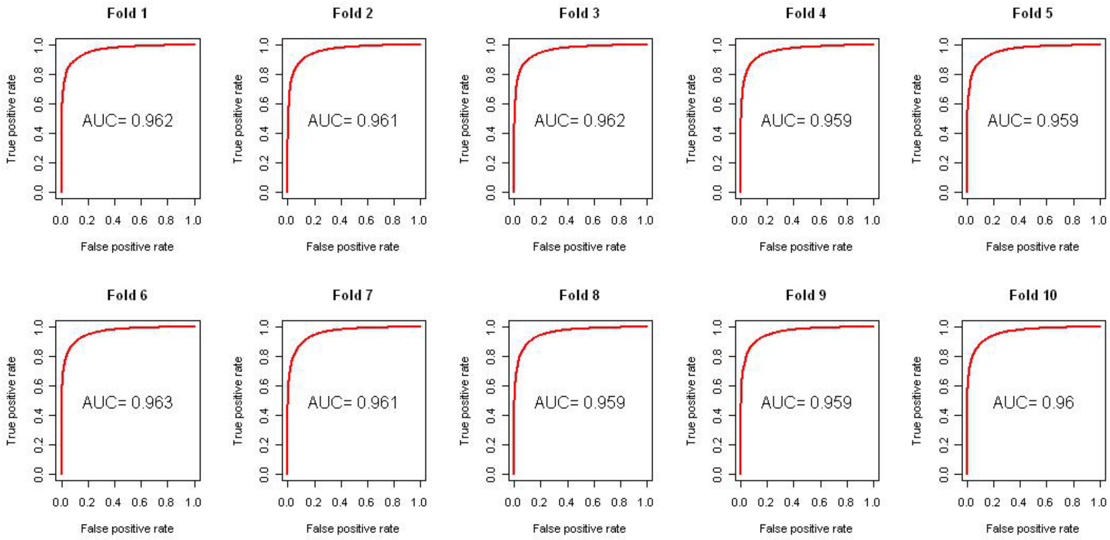
7.1 Assessing model fit

The ‘out-of-bag’ error rates generated during the random forest fitting process were used as estimates of misclassification error rates. These measures estimate the misclassification rate of model predictions during the fitting process based on cases excluded as part of the bootstrapping process (sampling with replacement). To get an overall estimate, the out-of-bag error rates was averaged over the ten folds. Before choosing this approach, these estimates of error were first compared with those obtained by using the ‘hold-out’ fold to predict for the remaining data—a much slower process. As predicted by Breiman (2001), the results were similar.

Data mining techniques are vulnerable to over-fitting. That is, variables may be included during the training phase that have no predictive power during the test phase. To satisfy our own curiosity regarding the possibility of random forests over-fitting, a simulated dataset was generated of the same dimensions as the training data. It consists of randomly generated presence/absence data and randomly generated uncorrelated explanatory variables. The resulting OOB error rates were consistently close to 0.5, as should be expected based on guessing as there is no information in the predictor variables. Care should be taken: confounding can occur for non-statistical reasons—assigning null animal distributions to a landscape invariably results in correlations with some bio-climatic variables if you examine enough of them (Beale et al 2008).

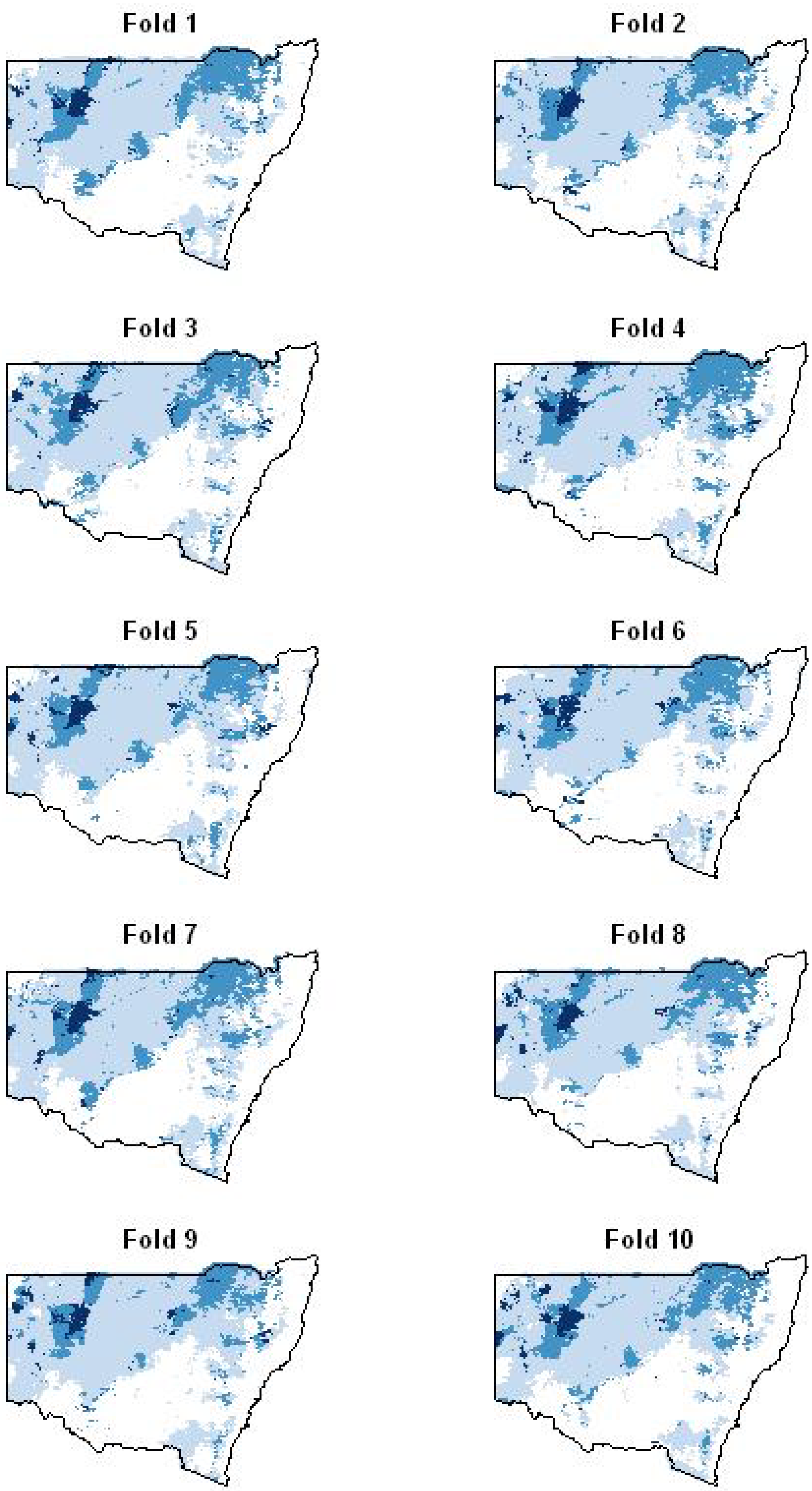
For comparative purposes, areas under the receiver operating characteristic curves (AUC) are also presented for presence/absence models. For each fold, predictions were undertaken for the remaining dataset, receiver operating characteristic curve was generated and the associated area under the curve estimated (Figure 1), and the AUC value of each averaged to get an overall AUC value.

Figure 1. Receiver operating characteristic curves arising from modelling feral pig presence/absence using the 10 data folds.

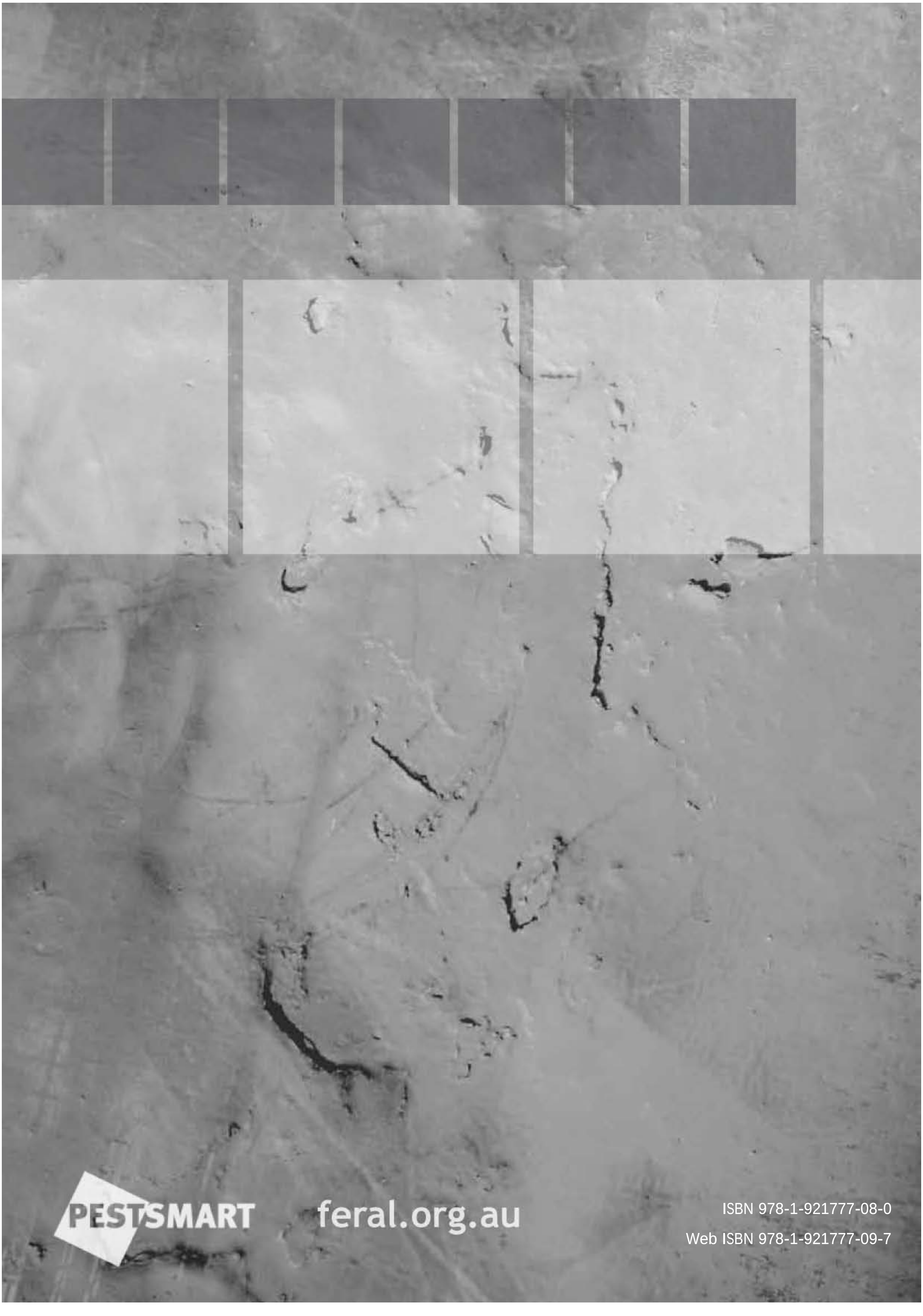


Combining fold-based model predictions

The model built using each fold was used to predict pest densities for each cell. Hence there were 10 forecast values for each cell (Map 23). These were used to obtain a ‘model-averaged’ forecast for each species by rounding the 10-fold mean to an integer value (0-3) for pest animal models and using the mode for nominal data (land use).



Map 23. The year 2004 density of feral pigs modelled from each of 10 independent folds selected from the dataset. The light, medium and dark shadings of blue represent ‘low’, ‘medium’ and ‘high’ density, respectively, with white shading indicating absence.



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